MAKING A HABITABLE PLANET FROM THE PERSPECTIVE OF ASTRO/COSMO/ GEOCHEMISTRY

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images: Hacar+ 2015; Pinte+ 2016; Louvet+ 2018
Andrews+ 2018; NOAA

The Ingredients for a Habitable World

at right distance from star

liquid water

elements of life
Carbon, Hydrogen
Oxygen, and Nitrogen

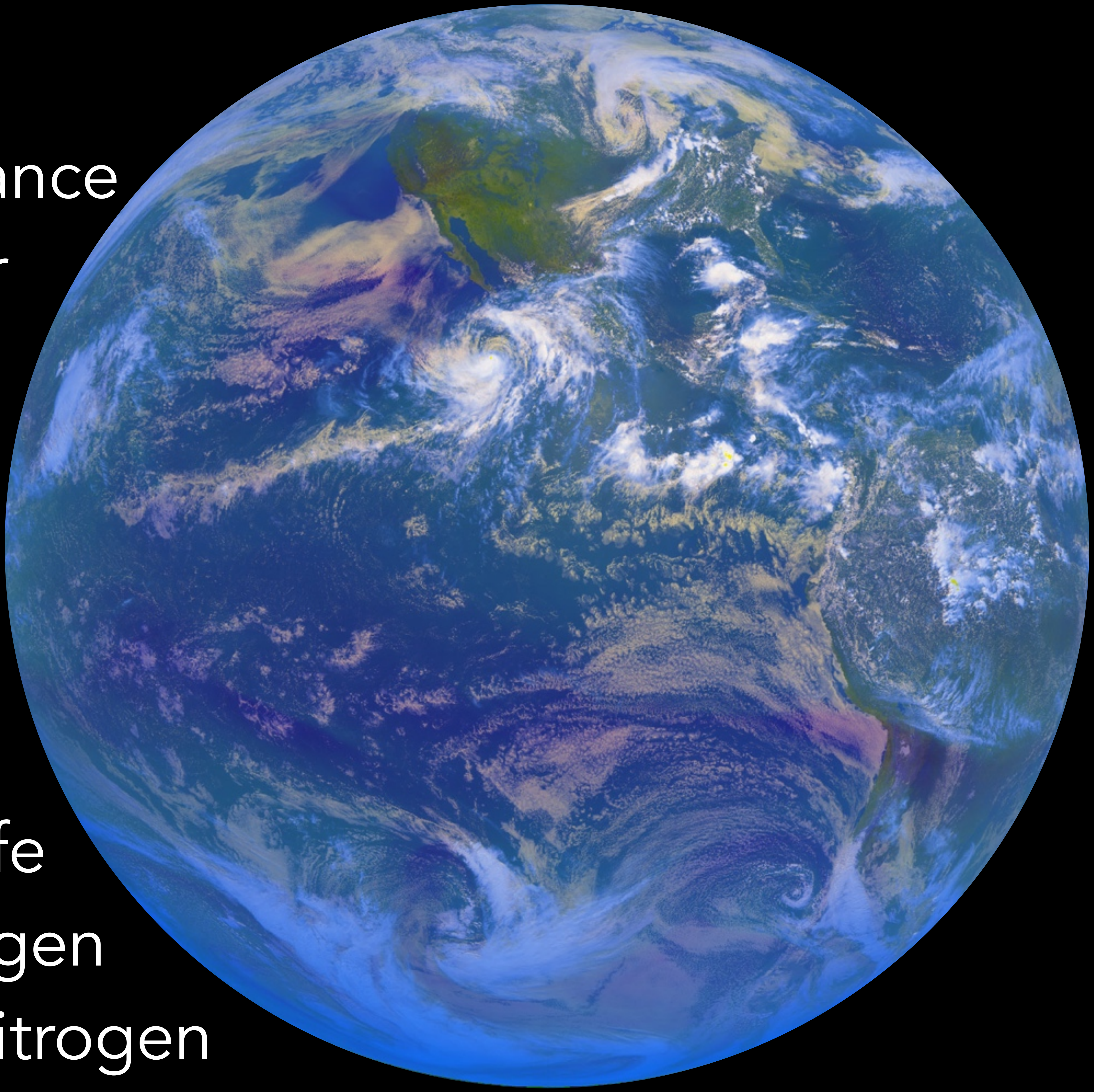


image credit: NOAA

How can we make connections from astronomy to planets/exoplanets?

Tracing Chemical Origins

- For terrestrial worlds and giant planets: difficult to determine what was provided when and in what form.
- For C and N carriers it is easier to concentrate on BULK composition (if possible).
  - i.e. not worrying about a particular organic needed to make RNA
- Oxygen is an important outlier in this regard as we know it was provided as H_2O + silicates.
- Could also discuss isotopic evidence (e.g. D/H, an oxygen isotopes) as evidence of origins…

TERRESTRIAL PLANET FORMATION

1 M_{Earth}
(6000 km)

Embryos
(Mars mass)

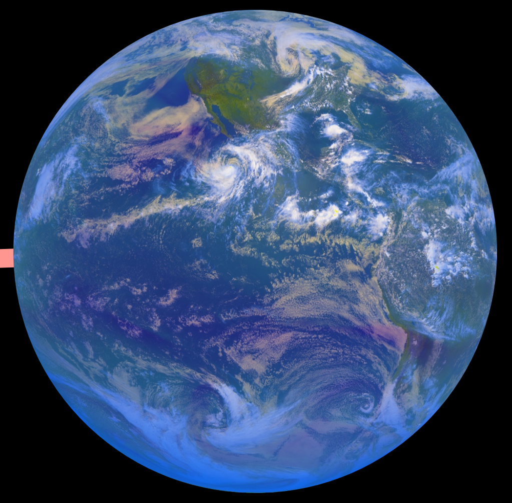
Planetesimals
(~100 km)

Dust (1 μm
or ~10^{-9} km)

~0.1-0.3 Myr

10 Myr

100 Myr



numerous *potential loss terms -*
drift/sublimation;
internal heating in planetesimals;
collisions; core formation;
atmospheric loss

need *to understand key processes first!!!*
talk to experts who have studied
our planet

focus *on key elements:*
C, O(H), N, S (and P)

adapted from Meech & Raymond 2019; see also Johansen & Lambrechts 2017 and Morbidelli 2018

What is $t=0$?
How do we trace "time" in the evolution?

LEAD-LEAD DATING and t=0

- ^{238}U(99.27%) decays to ^{206}Pb half-life of 4.47 Byr
- ^{235}U(0.72%) decays to ^{207}Pb half-life of 0.704 Byr
- ^{232}Th(100%) decays to ^{208}Pb half-life of 14.1 Byr

U-Th-Pb governing equations

$$\frac{^{206}Pb}{^{204}Pb} = \left(\frac{^{206}Pb}{^{204}Pb}\right)_i + \frac{^{238}U}{^{204}Pb}(e^{\lambda t} - 1)$$

$$\frac{^{207}Pb}{^{204}Pb} = \left(\frac{^{207}Pb}{^{204}Pb}\right)_i + \frac{^{235}U}{^{204}Pb}(e^{\lambda t} - 1)$$

$$\frac{^{208}Pb}{^{204}Pb} = \left(\frac{^{208}Pb}{^{204}Pb}\right)_i + \frac{^{232}Th}{^{204}Pb}(e^{\lambda t} - 1)$$

* Note that in all three decay schemes, ^{204}Pb is used as a reference isotope - as it is entirely primordial

- what is the initial state? what is the initial expected isotopic ratio that the rock started with? No rocks on Earth can provide this ratio.
- C. Patterson used the Canyon Diablo meteorite which had very low values of the Pb daughter products and also low in Uranium relative to Pb
- provided primordial isotope ratios and unlocked t=0

CORE FORMATION

- Hf = lithophile, W = siderophile
- Decay half-life is 8.9 Myr
- If core forms early then all W in mantle is from Hf decay.
- If core forms late then Hf decay creates ^{182}W which goes to core.
- If core formation occurs during the frame where Hf decay is active then you have the date of Earth solidification.

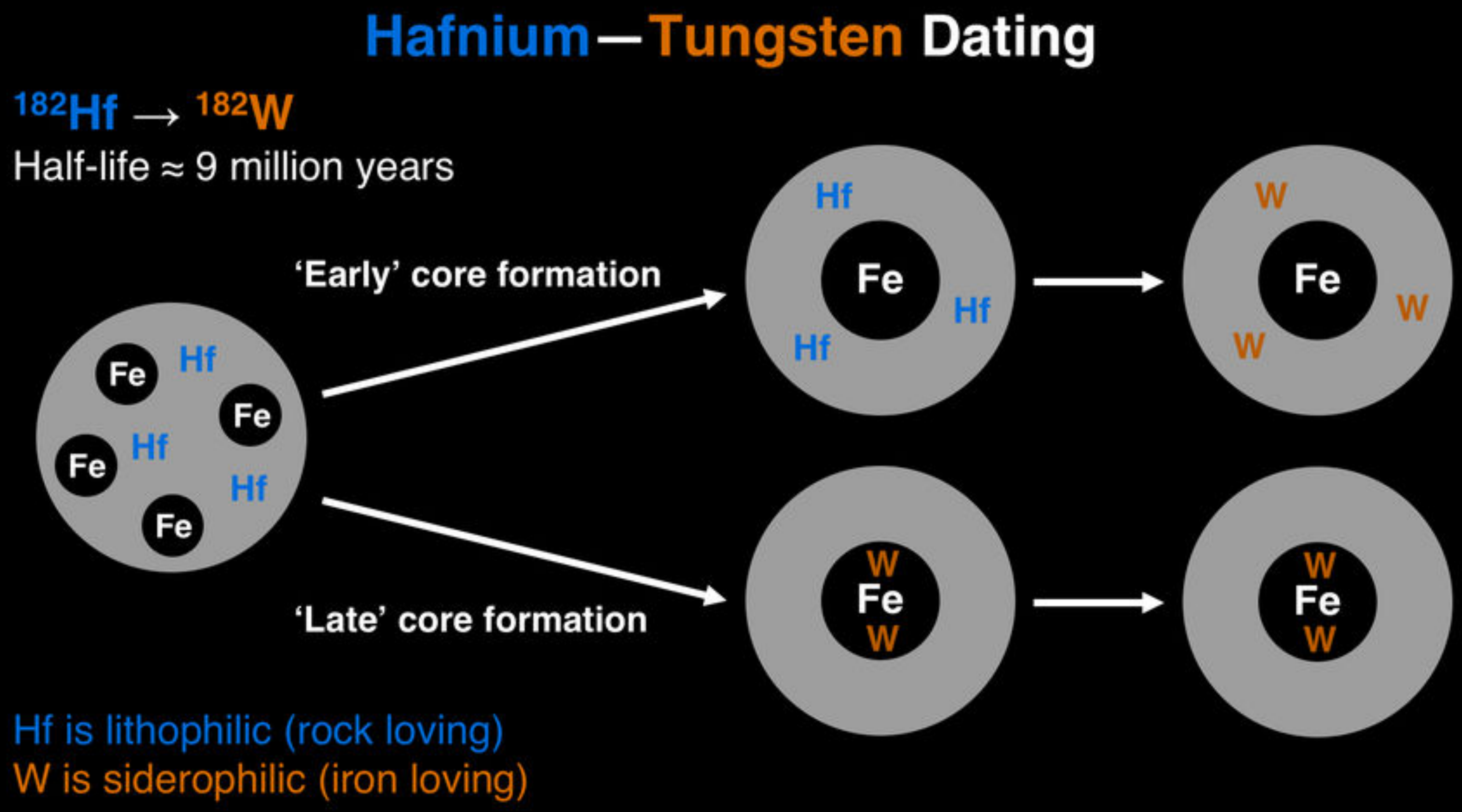
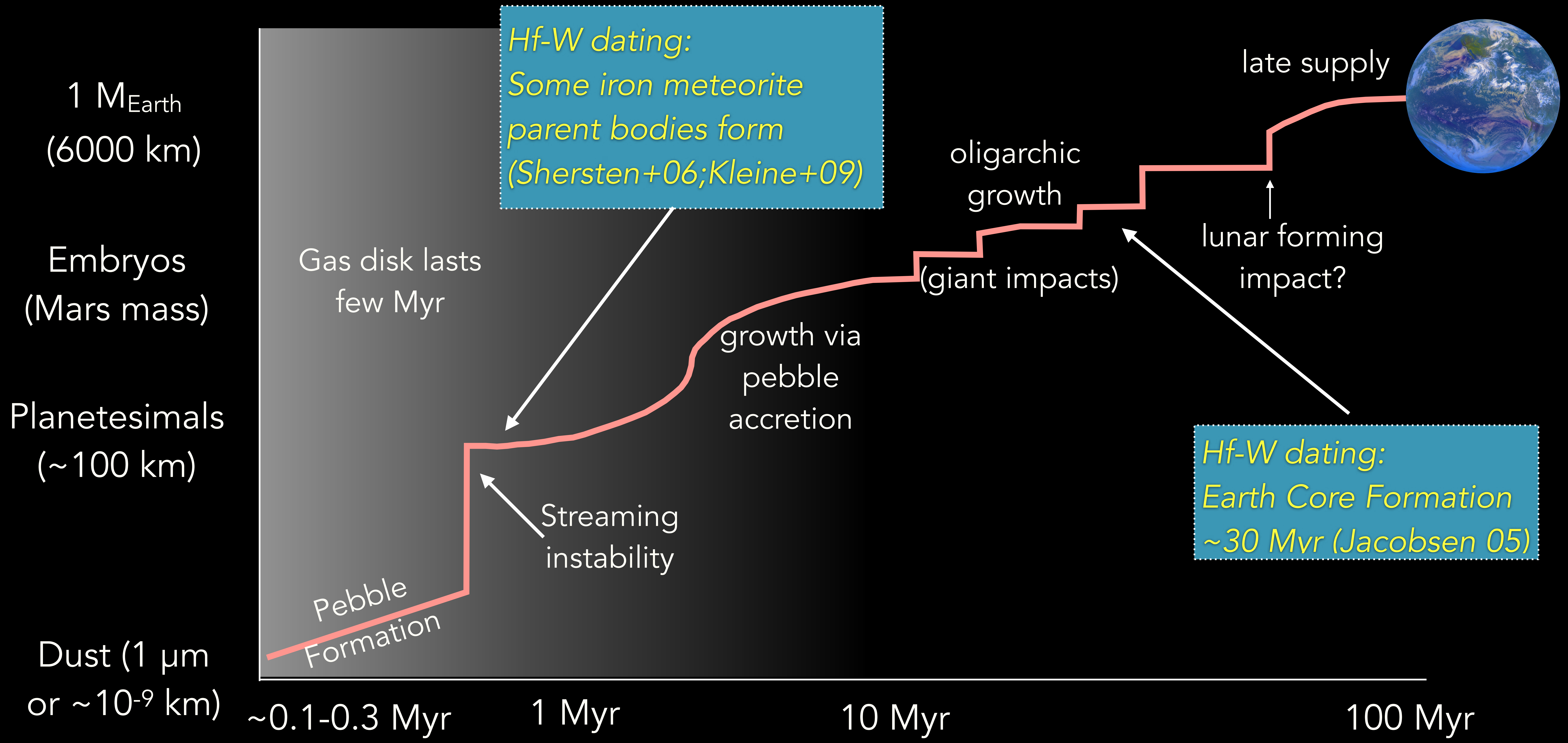


image from wikipedia

core formation estimates are ~30-40 Myr but could be as much as 100 Myr assuming variable accretion events (Dauphas and Chaussidon 2011)

for more explicit details see Wood 2011 for discussion

TERRESTRIAL PLANET FORMATION



adapted from Meech & Raymond 2019; see also Johansen & Lambrechts 2017 and Morbidelli 2018

WATER WORLD?

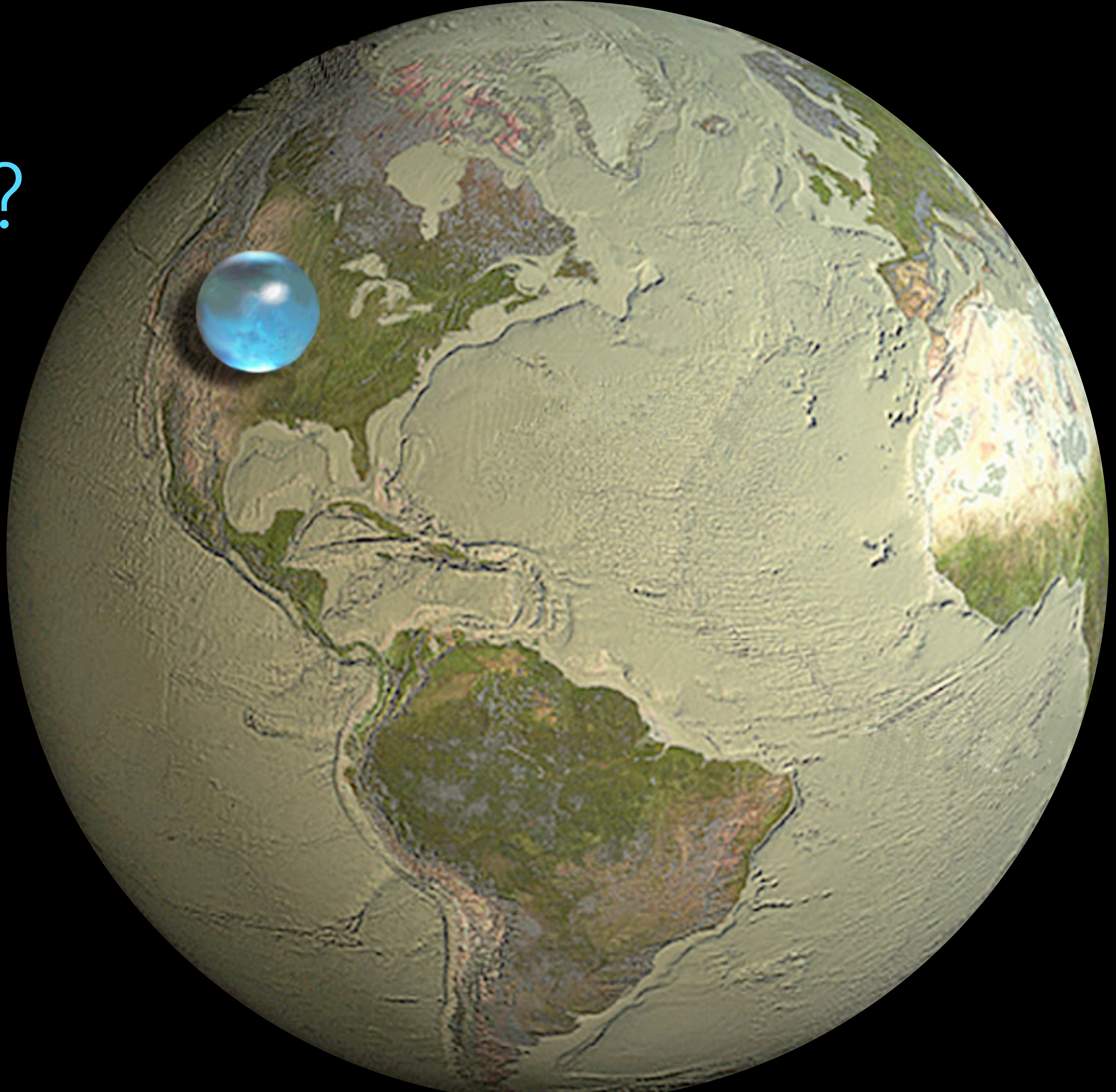


image credit: NOAO +
Jack Cook (Woods Hole) & Howard Perlman (USGS)

CARBON-BASED LIVING PLANET

The Earth received less than 1 carbon atom per 10000 available

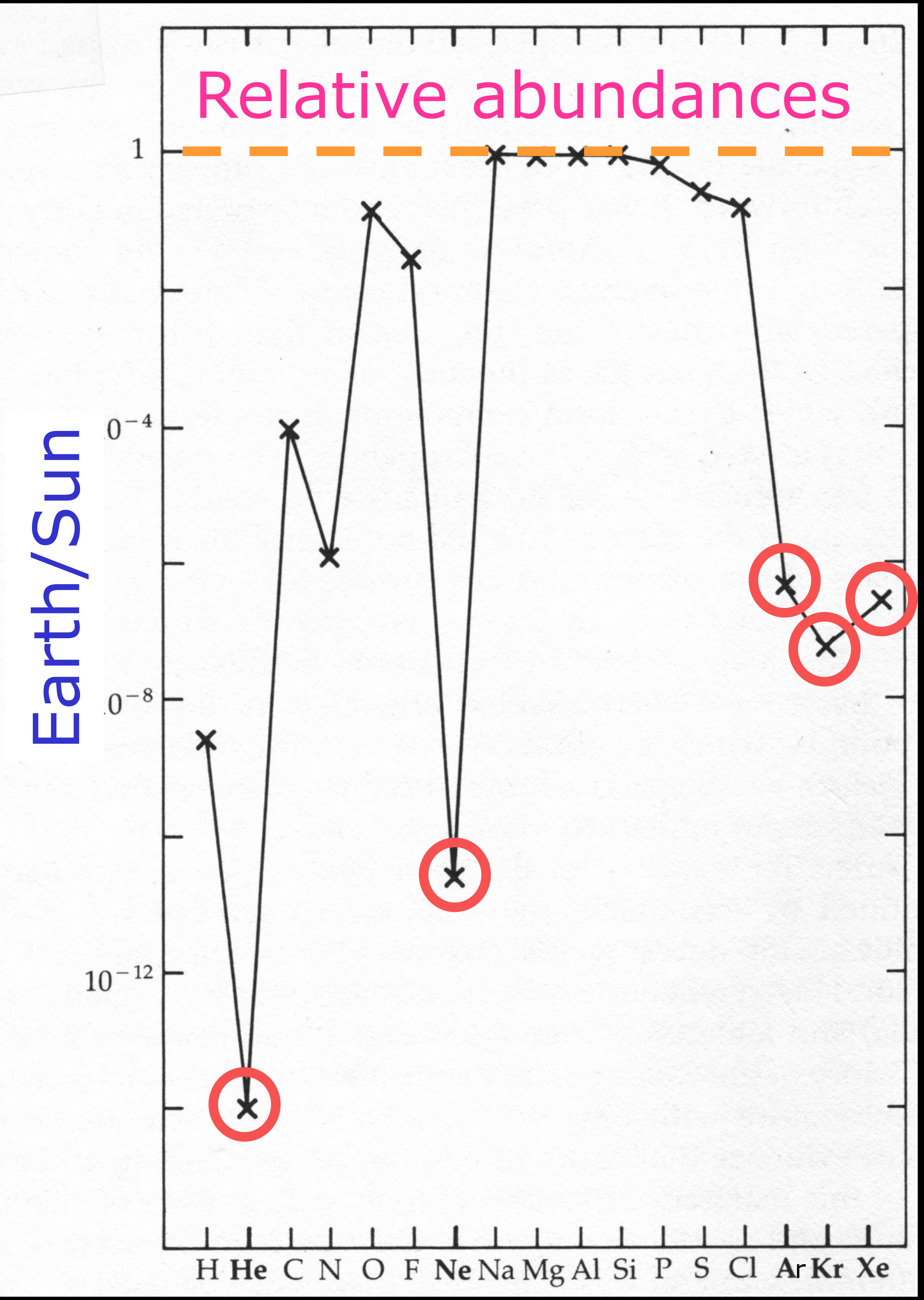
less than 1 N atom per 100000 available

We are a silicate rock with a tiny sprinkling of carbon, nitrogen and some water.

How did this happen? Is this common?

‘SECONDARY’ origin of terrestrial world atmospheres?

Slide from D. Catling



1) Noble gases ( ) severely depleted

- negligible gas from solar nebula (e.g., very little neon)
- atmospheres derive from solids

H_2O - hydrated minerals

C - hydrocarbons (+carbonates?)

2) Theory:

- pre-main sequence *T-Tauri* phase ~10^7 yr blows away any accreted primary atmosphere + hydrodynamic escape

- planet formation from protoplanets (10^3-10^4 km size)

OUTGASSING, INGASSING, AND DEGASSING

Slide from D. Catling

[Qu.) What is a volatile?

relatively low melting or boiling points, so that they are present as liquids or gases in a planet's hydrosphere or atmosphere. Same concept for disk but sublimation/deposition is the process.

Old Ideas:

Outgassing by volcanoes: William Rubey, USGS (1955) and subsequent workers presumed that the atmosphere and oceans were derived this way after the Earth formed

Current Ideas:

Impact degassing:

Once Earth reaches ~1/3 present mass, volatiles in accelerated bolides get vaporized. Atmosphere starts to form as the planet forms, then ocean condenses.

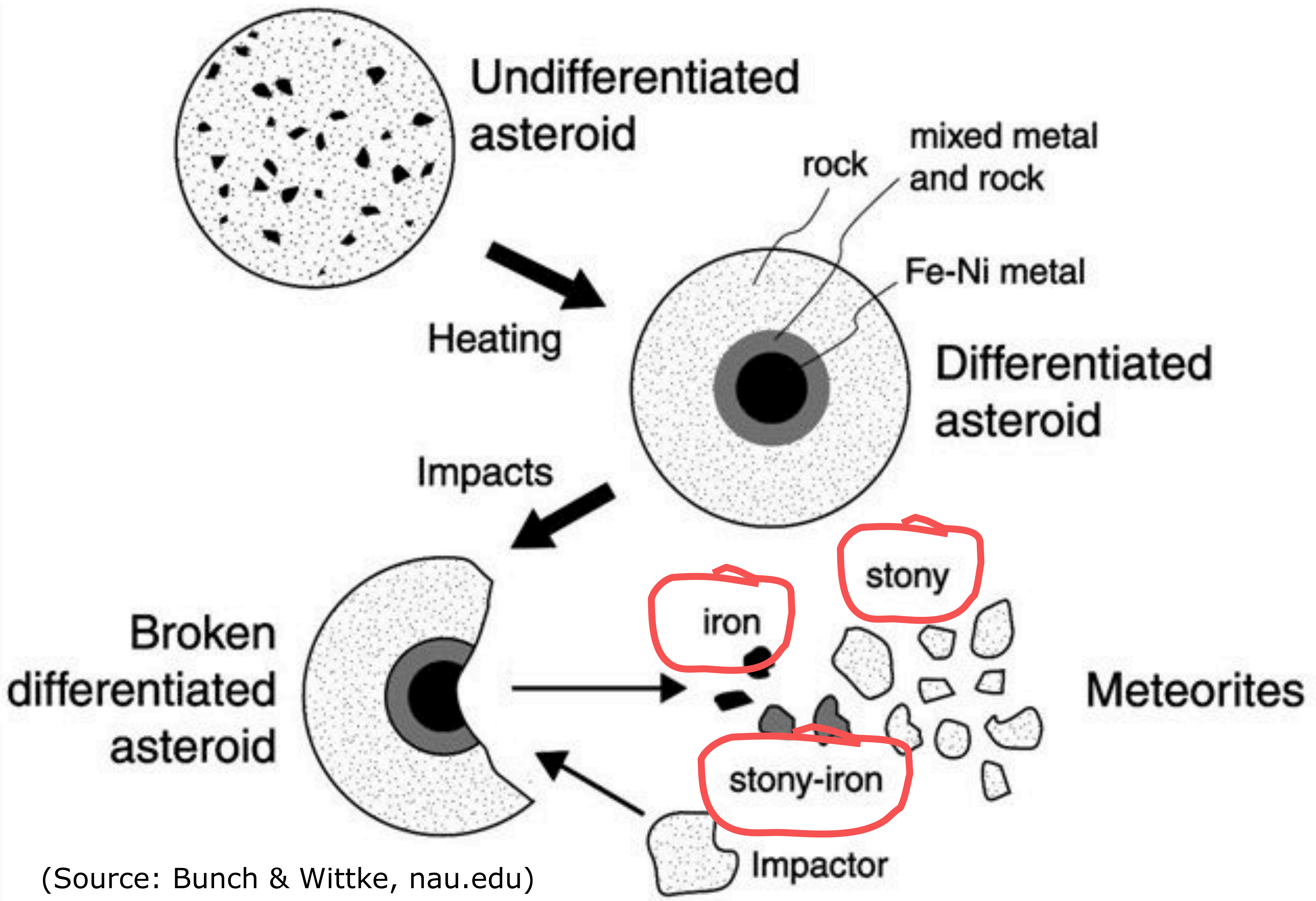
Ingassing:

On Earth, at least, some volatiles have returned to the interior, e.g., carbon.

If impacts ->atmospheres, meteorites must provide clues

Slide from D. Catling

Types of meteorite



(Source: Bunch & Wittke, nau.edu)

BASIC TYPES OF METEORITE

Slide from D. Catling

1) Irons – predominantly iron.

2) Stony – predominantly silicates.

(a) >90% chondrites, i.e., contains chondrules (globules of silicate minerals, up to a few mm size, interpreted as rapidly cooled silicate melt formed by condensation of melted dust in the nebula).

- Ordinary chondrites, 5-15% Fe-Ni
- Carbonaceous chondrites, C-rich

(from Beatty et al., The New Solar System, Ch. 26)

(b) achondrites do not contain chondrules and formed from igneous rocks of their parents (e.g. Martian meteorites)

3) Stony-iron – silicate and iron mixture.

HOW MUCH VOLATILE MATERIAL? TAKE WATER AS EXAMPLE

Region	Low [Oceans]	High [Oceans]	Capacity [Oceans]
Hydrosphere	1.2	1.2	1.2
Sed. Rocks	0.2	0.20	0.1
Upper Mantle	<0.02	< 0.02	3.3
Lower Mantle	0.04	1.8	15.1
[Core	0.03	2.8	28.1]
TOTAL BSE	1.6	3.2	59.7

Mottl et al. 2007
Slide from
K. Meech

VOLATILES, METEORITES, AND OCEANS

Slide from D. Catling

- Carbonaceous chondrites
  - Up to 20 wt.% H_2O
  - ~3.5 wt% organic C, 0.3 wt%N
  - Carbonaceous chondrite Earth:

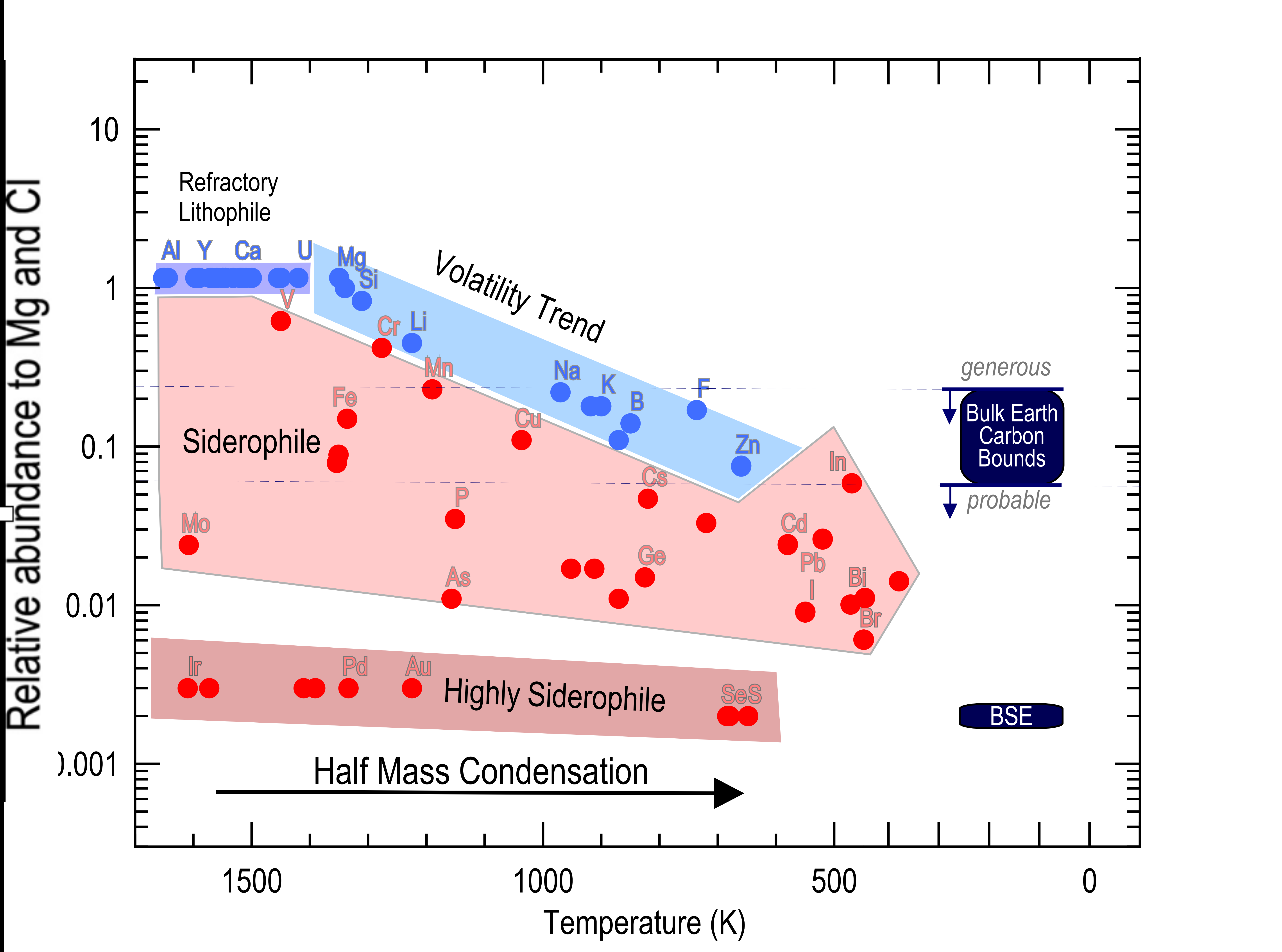
    6 x10^{24} kg (x 0.15) = 9 x10^{23} kg ~ 600 oceans

- Ordinary chondrites (97% of all chondrites in collection)
  - ~0.1 wt% H_2O, ~0.03 wt% N, ~0.1 wt% C
  - Ordinary chondrite Earth:

    6 x10^{24} kg (x0.001) = 6 x 10^{21} kg ~ 4 oceans

=> A few planetesimals with carbonaceous chondrite composition suffice

VOLATILITY TREND AND THE CONDENSATION SEQUENCE



Li, Bergin, Blake, Ciesla, & Hirschmann 2020

THE "CONDENSATION MODEL" (JOHN LEWIS)

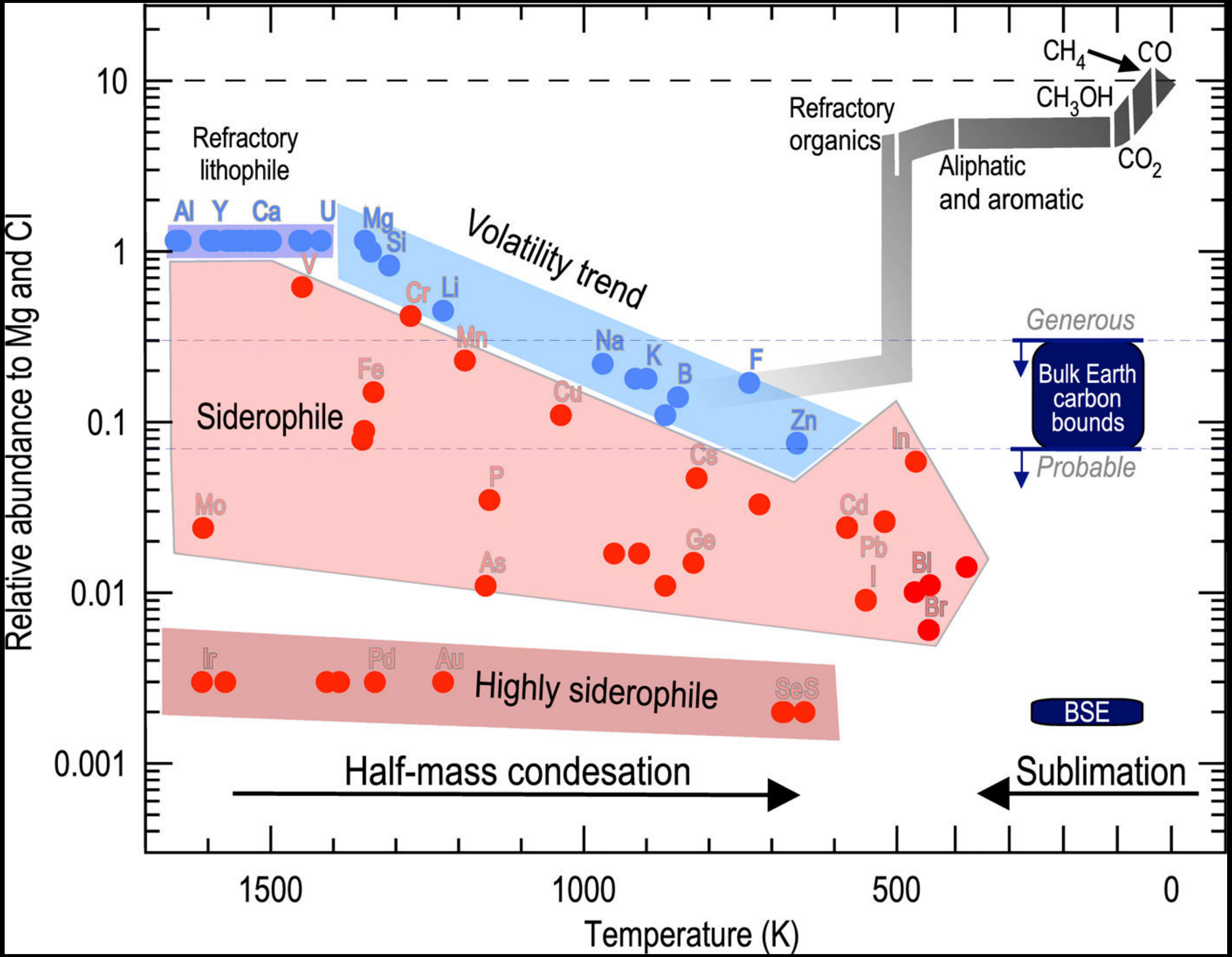
Slide from D. Catling

Temp/ K	Substance	General groups (Comments)
~1800	Highly refractory metals, W, Os, Ir, Re	*Refractory metals*
1677	Corundum, Al_2O_3	*Refractory oxides*
1593	Perovskite, $CaTiO_3$	
1397	Spinel, $MgAl_2O_4$	
1360	Nickel-iron metal, Ni, Fe	*Ni-Fe (core forming metals)*
1347	Pyroxene, $CaMgSi_2O_6$ (diopside)	*Silicates (rock forming minerals)*
1354	Olivine, Mg_2SiO_4 (forsterite) or Fe_2SiO_4 (fayalite)	
<1000	Alkali feldspars, $(Na, K)AlSi_3O_8$	(60% of Earth's crust)
~700	Troilite, FeS	*Sulfides*. (Chalcophile (sulfur-loving) elements also include Zn and Pb).
550-330	Minerals with –OH or H_2O in their formulae	*Hydrated minerals*
	Ionic substances above ▲, Molecular substances below▼	
~180	Water ice, H_2O	*Ices* (Caveat: The form in which C or N condenses depends upon the availability of water and kinetics. If there is not enough water, they will not condense as clathrates, e.g., graphite could condense at higher temperature (Lodders, 2003)).
~120-130	Ammonia ice, $NH_3 \cdot H_2O$	
40-78	Methane ice, $CH_4 \cdot 7H_2O$ or CH_4 ice	
50-60	Nitrogen ice, $N_2 \cdot 6H_2O$ and $N_2 \cdot 7H_2O$	

MODERN PERSPECTIVE

- Accretion: outer disk is accreting unprocessed material.
- Pebbles:
  - ➡ Pebble accretion plays an important role in planet formation.
  - ➡ Pebble drift can supply material from greater distances (pending pressure structure of the disk).
  - ➡ Pebbles can lose volatiles via **sublimation** in hot inner nebula or during accretion to early atmosphere.
- Planetesimals:
  - ➡ Volatiles can be lost through metamorphic process and due to ^{26}Al decay.
- Planets: core formation and atmospheric loss.
- Mixing induced by interactions with giant planets.
- **Condensation and sublimation must play a role in early stages and parent body processes dominate later stages.**

CONDENSATION AND SUBLIMATION SEQUENCE

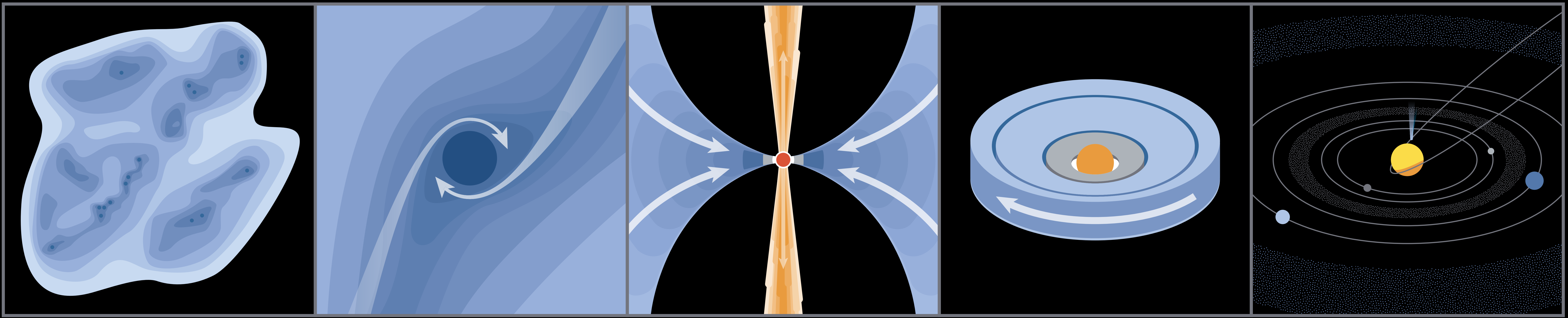


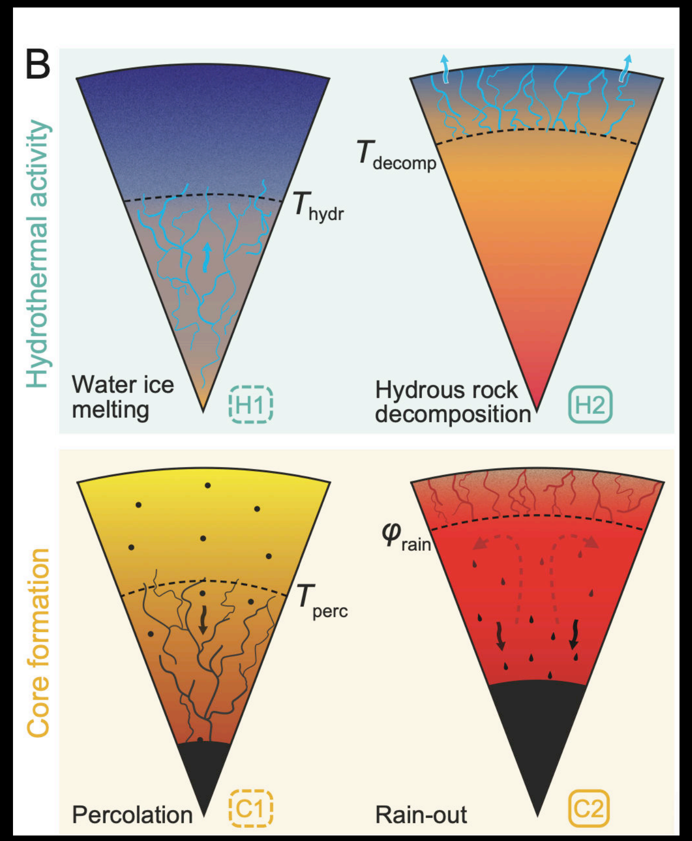
Li, Bergin, Blake, Ciesla, & Hirschmann 2020

GENERAL EVOLUTION

STAR & PLANET FORMATION

Cloud | Pre-Stellar Core | Protostar | Proto-Planetary Disk | Solar System

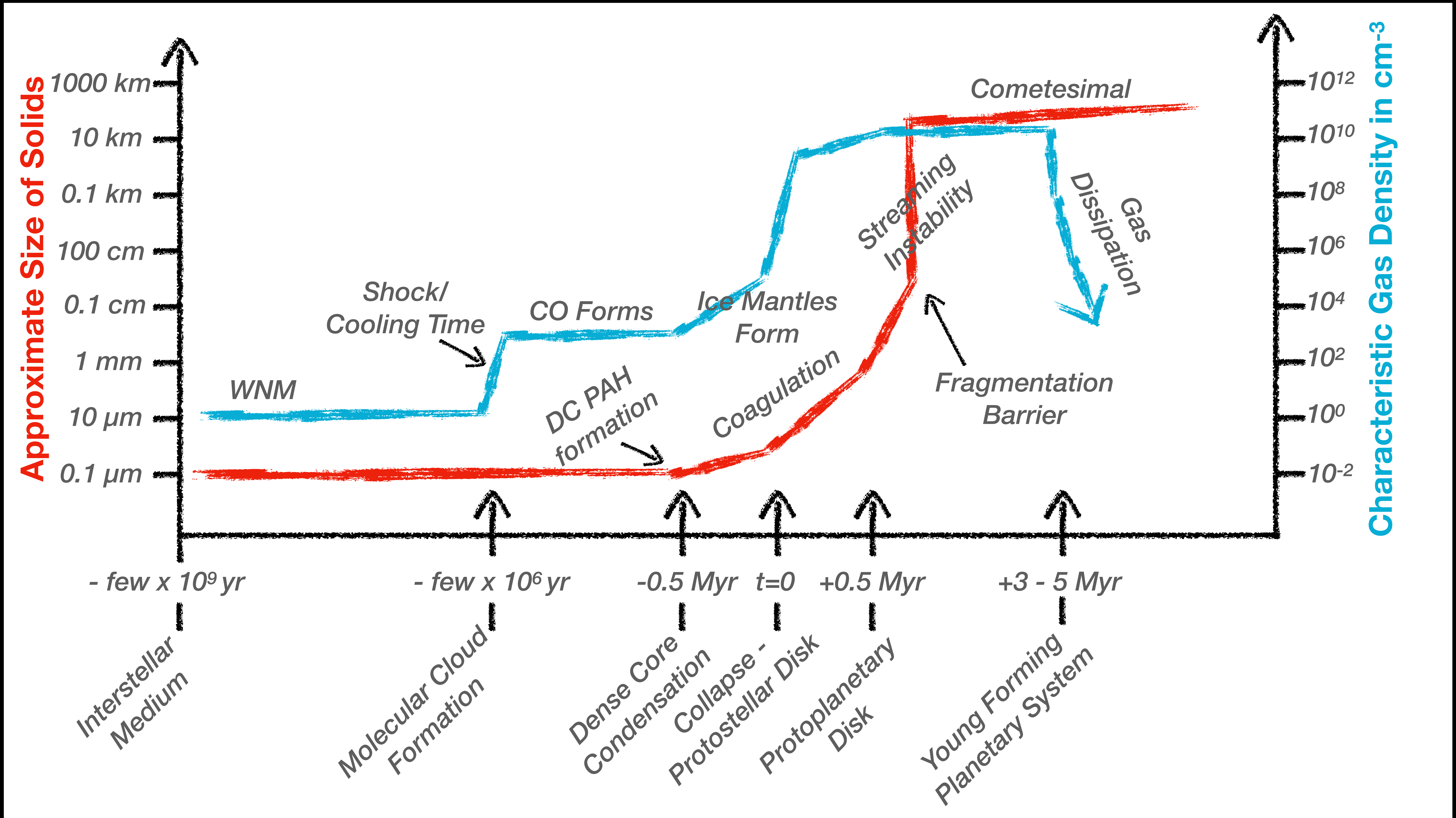




Öberg & Bergin 2021

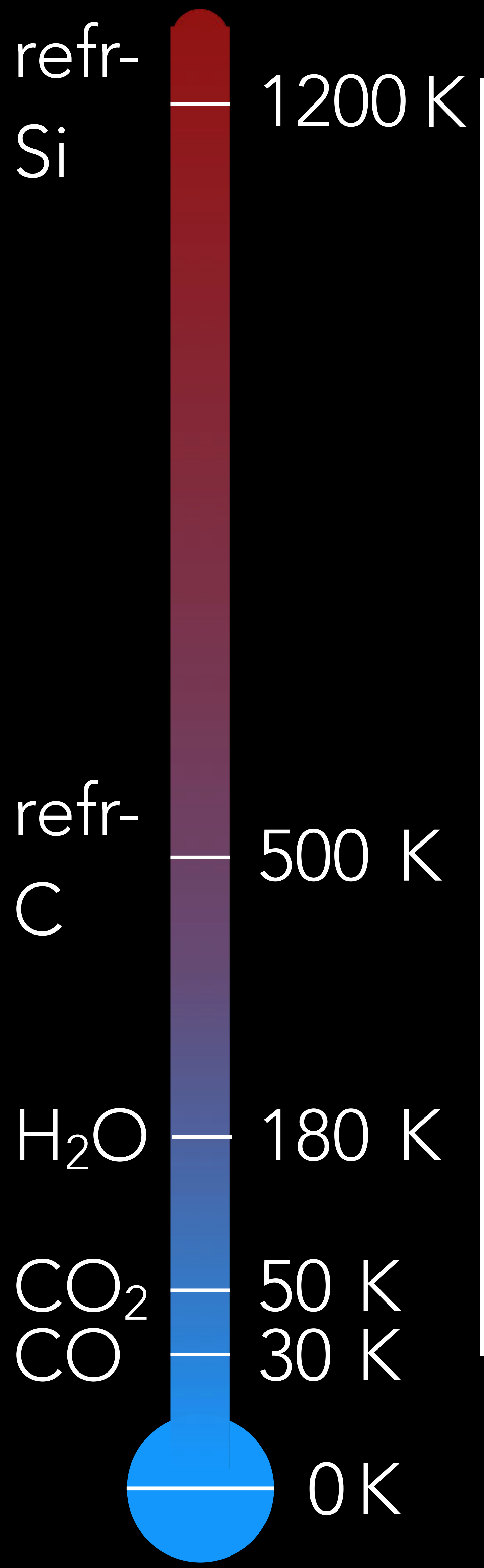
Lichtenberg et al. 2021

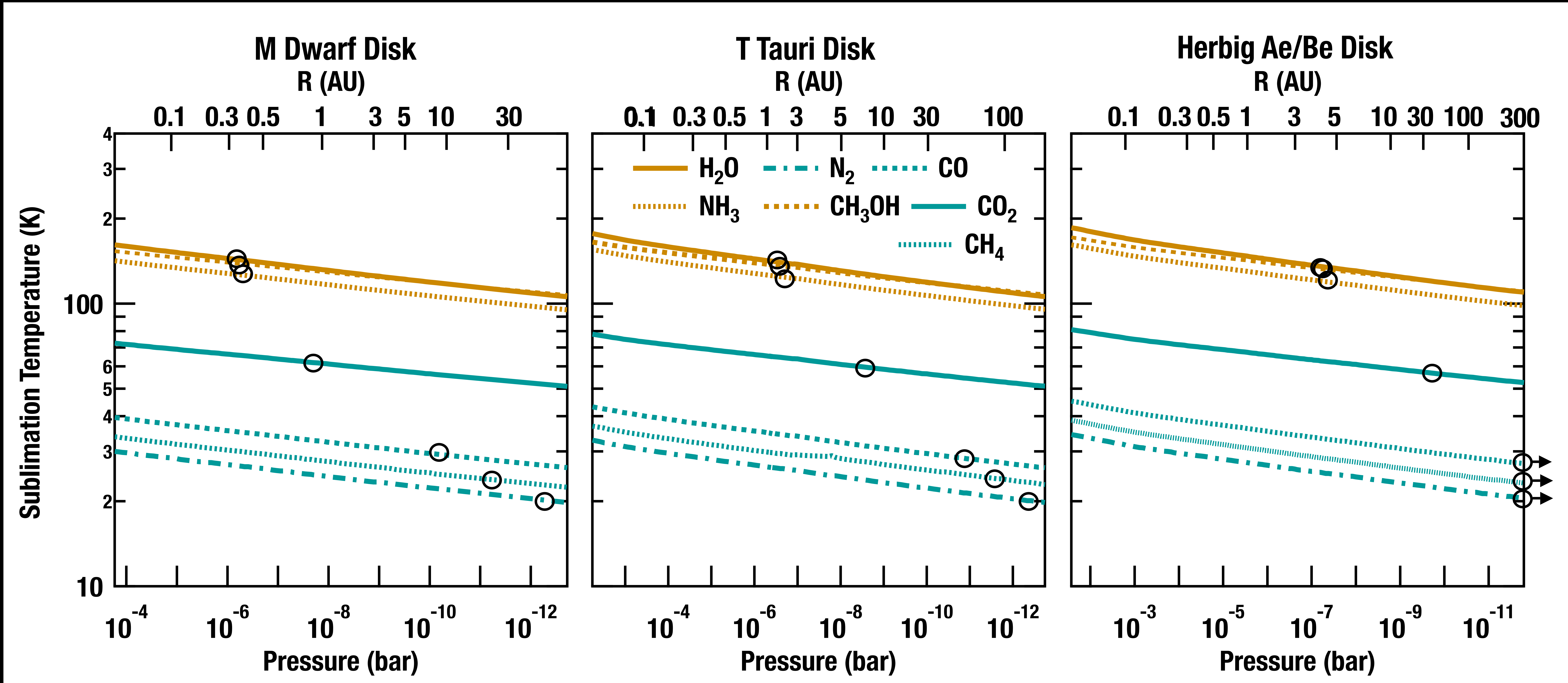
GENERAL EVOLUTION



Bergin, Alexander, Gounelle, & Drozdovskaya (in prep.)

WHAT IS IN SOLIDS(?) - SUBLIMATION





Minissale et al. (in prep.)

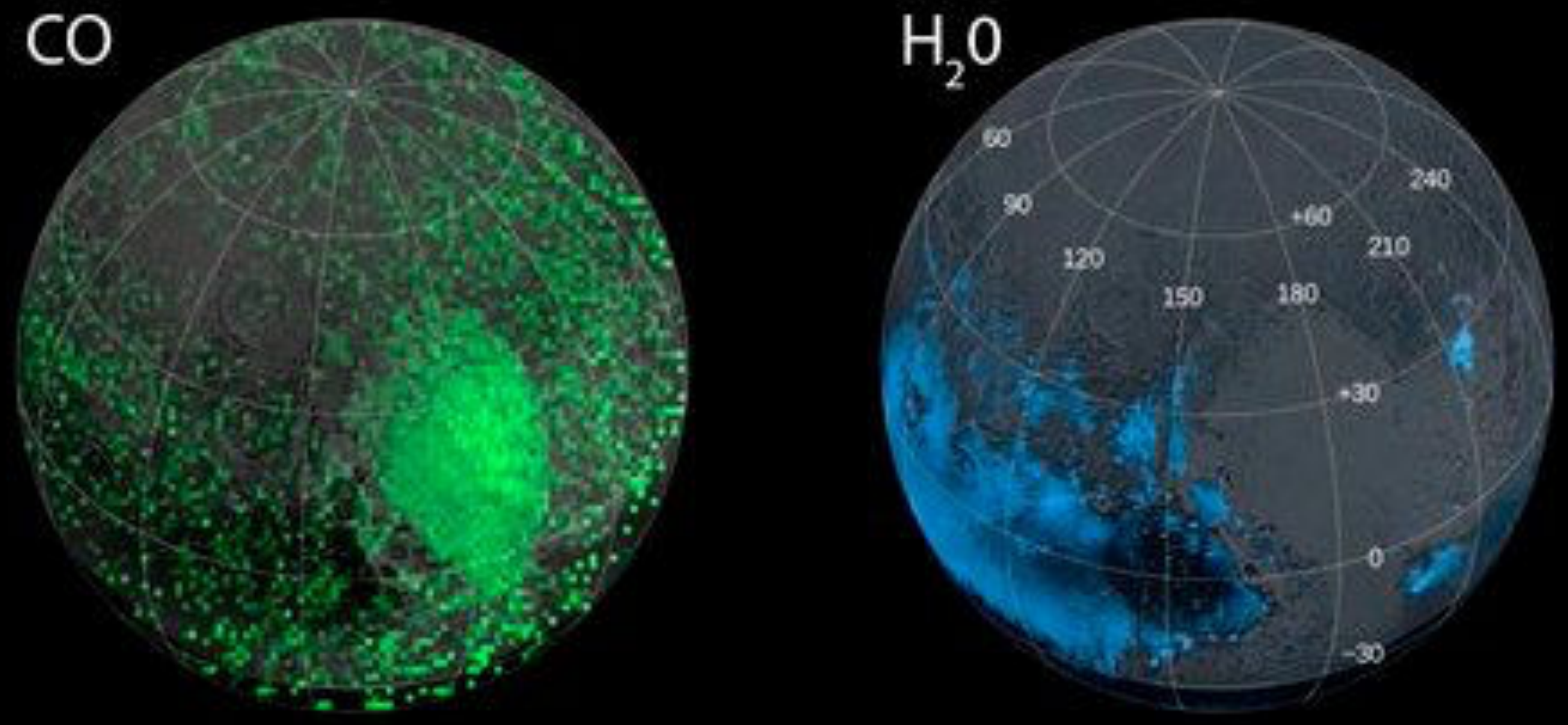
ELEMENTAL ACCOUTING

Note: Will focus on carbon for the most part. Nitrogen comes with carbon - and water is a related story.

BULK COMPOSITION CARRIERS

Refractory

Volatiles



Gladstone and others, 201
NASA/JHU APL/SWRI

(C) PAHs and/or aliphatic hydrocarbons

(O) Silicates

(C) CO, CO_2

(O) H_2O, CO, CO_2

20 pc
5 pc
0.1pc
100 au
1 au


Goldsmith+ 2008; Boogert+ 2015
20 pc
5 pc
0.1pc
100 au
1 au
CO
Refractory
Carbon
O I
H_2O_{ice}
CO
Silicates
Unknown
n_H ~ 3000 cm^{-3}
T ~ 20 K

DENSE PRE-STELLAR CORES

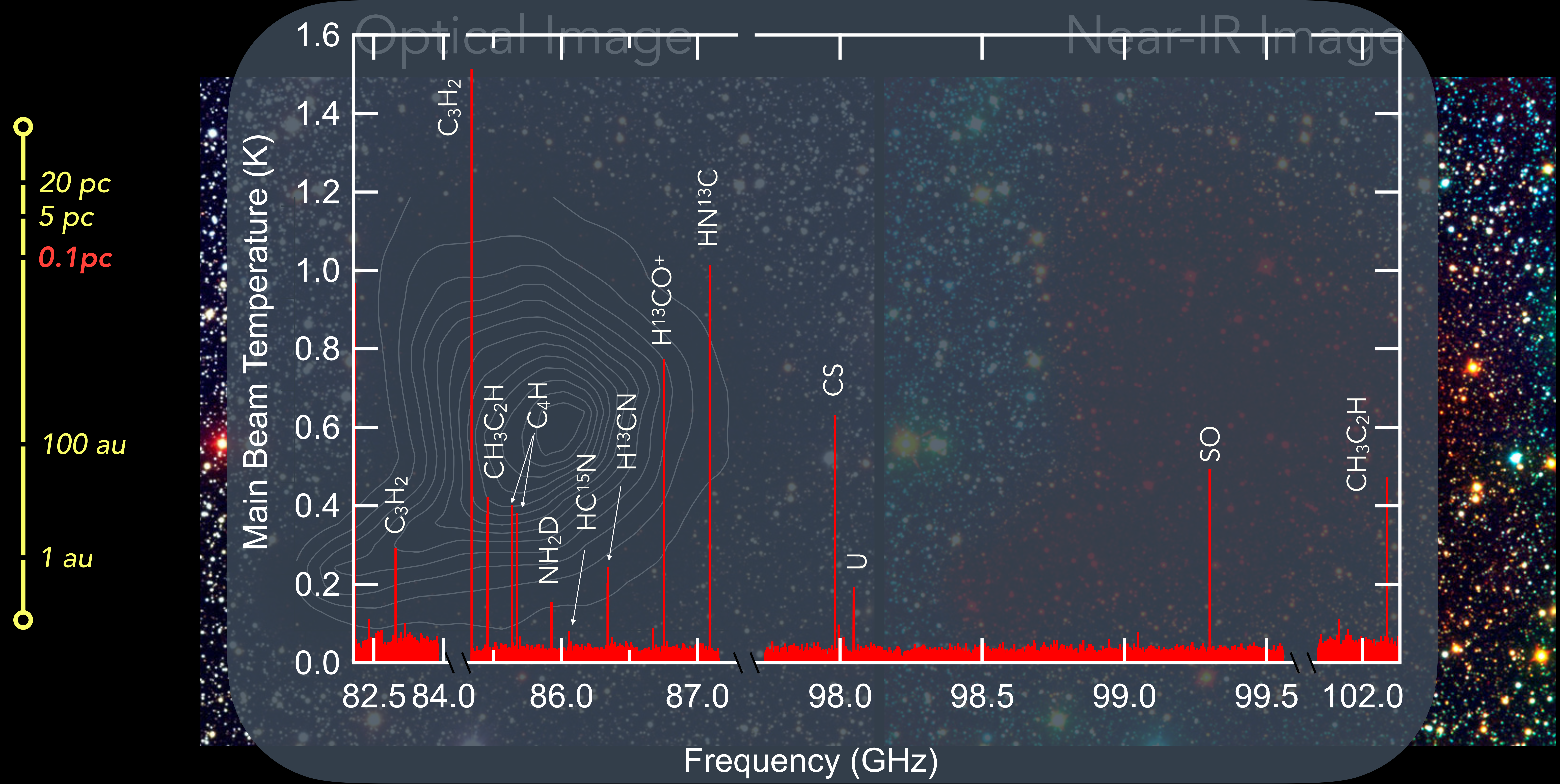
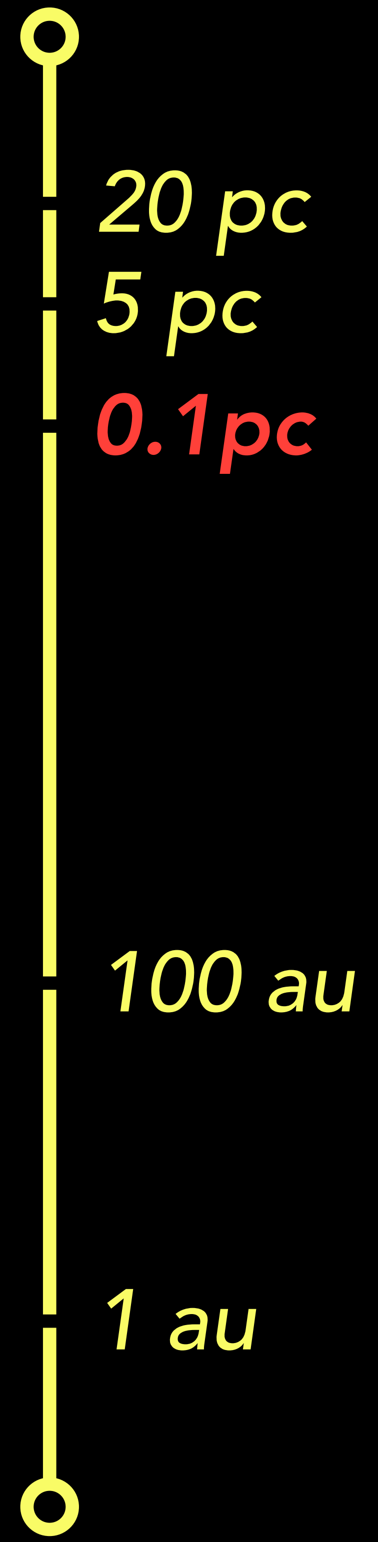
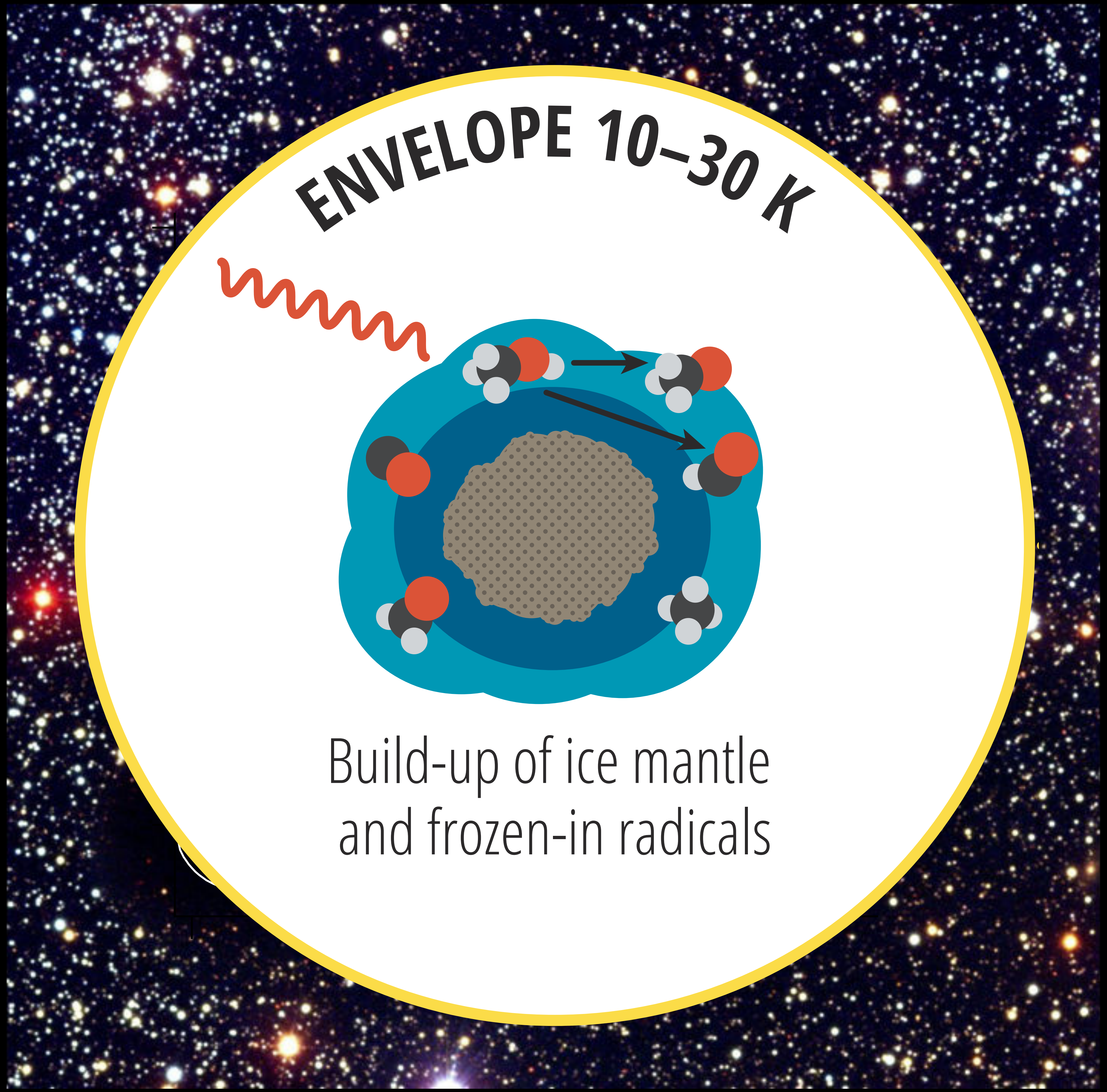
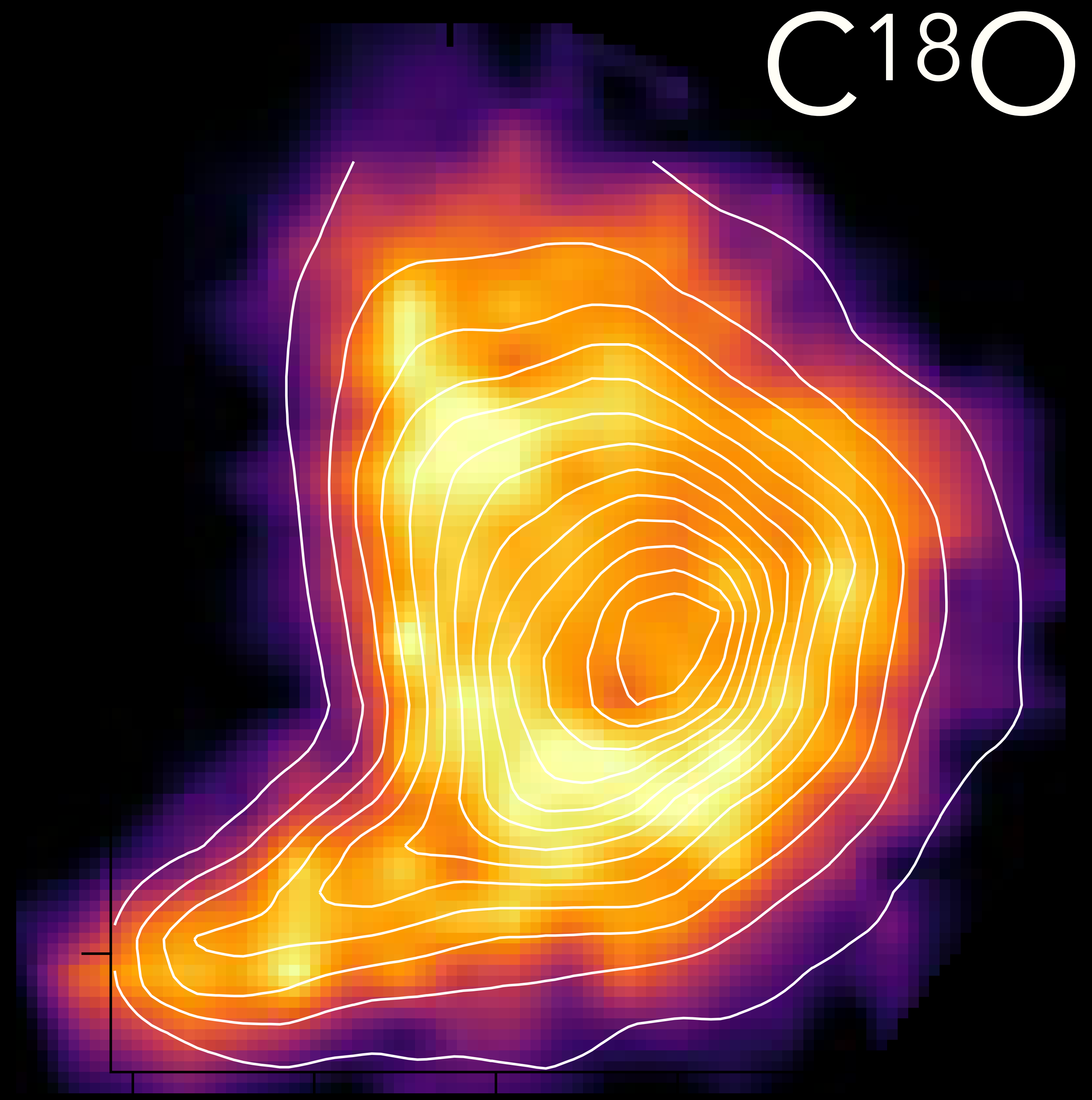


image credit: ESO; extinction map: Alves+ 2001

DENSE PRE-STELLAR CORES





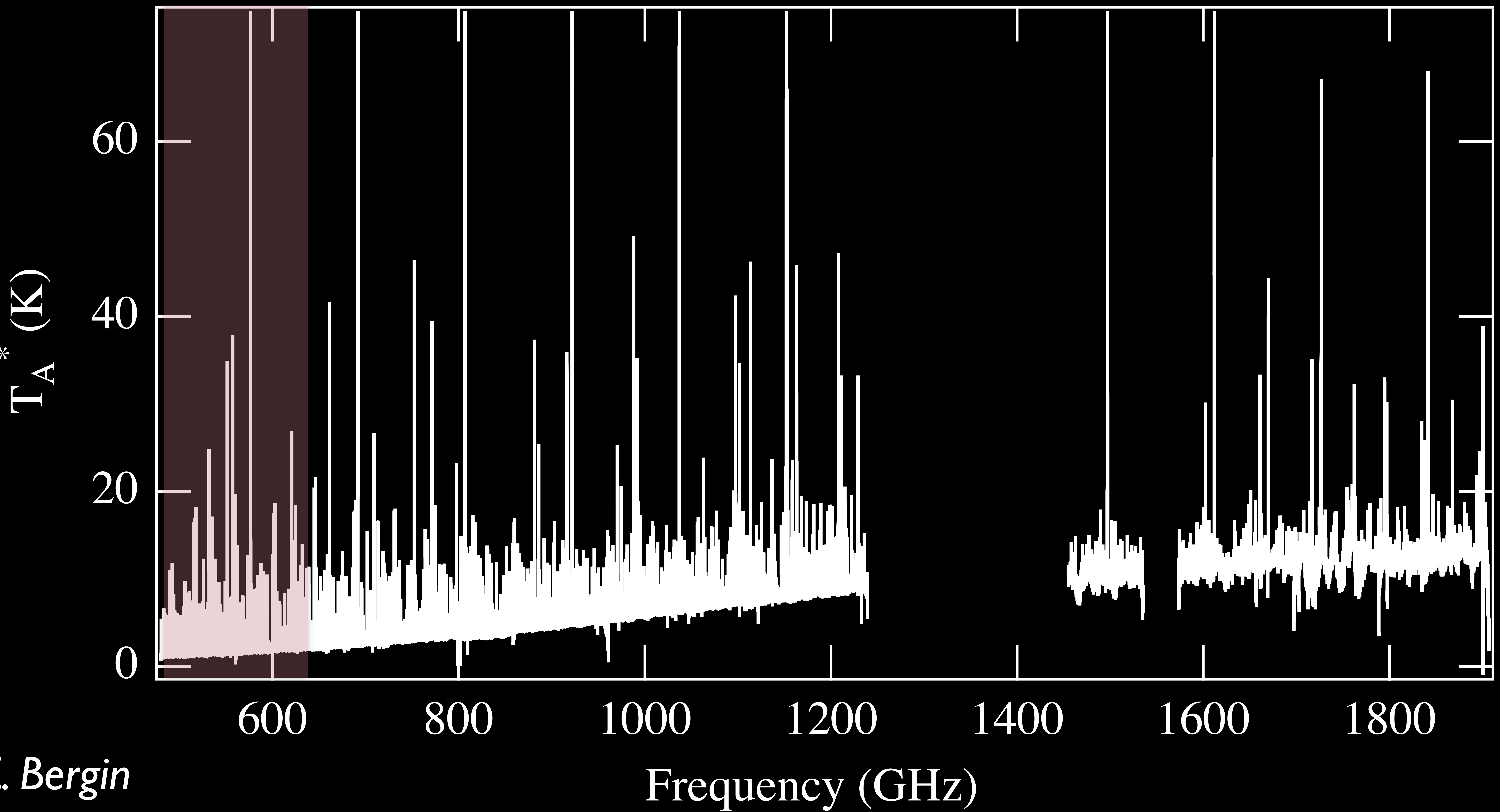


molecular emission images: Bergin+ 2002


Orion KL
image credit: ESO

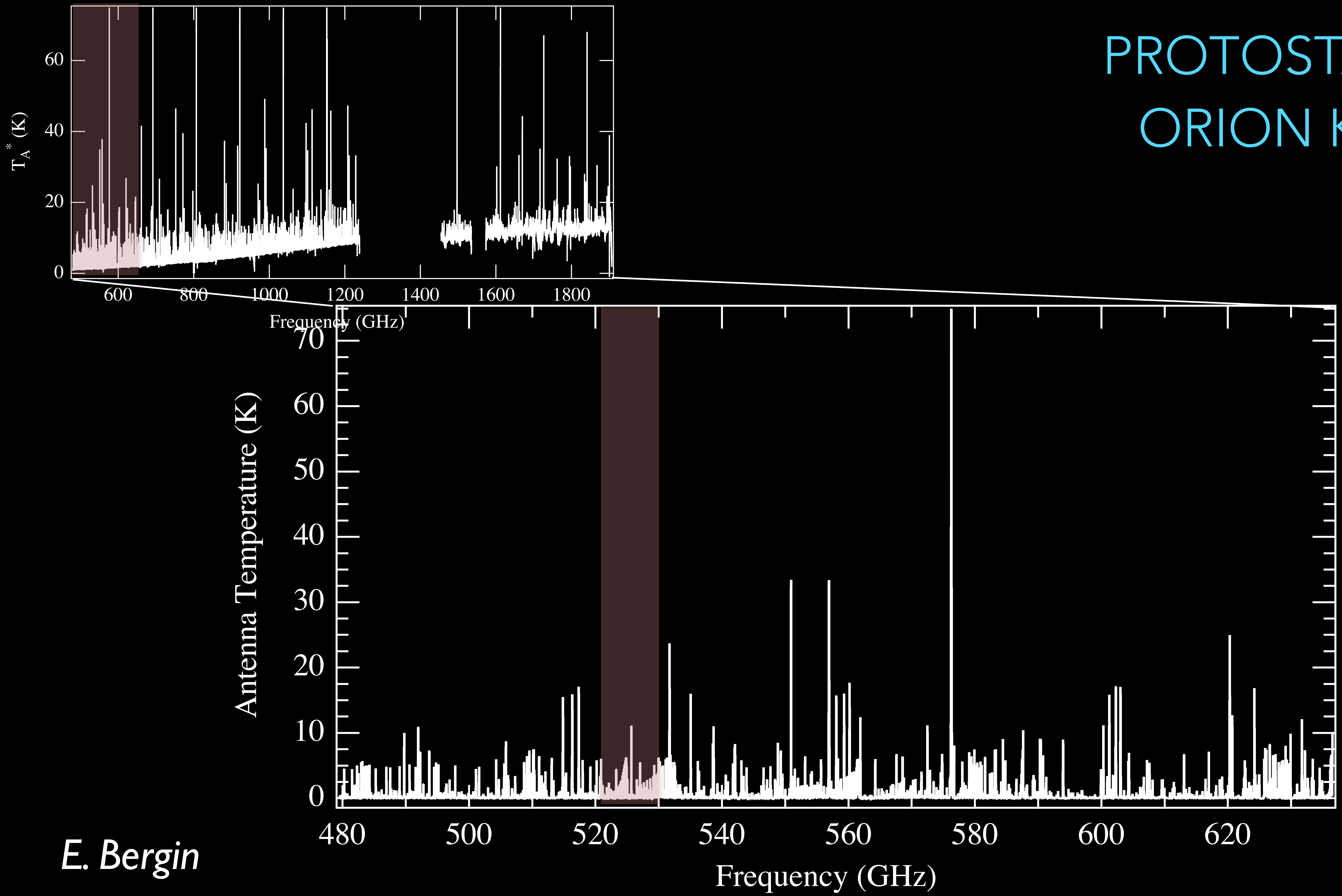
PROTOSTAR: ORION KL

- Angular resolution is ~45″ (460 GHz/652 μm) to ~10″ (1900 GHz/158 μm)
- Corresponds to 0.02 pc x (θ/10″) x (D/450 pc)



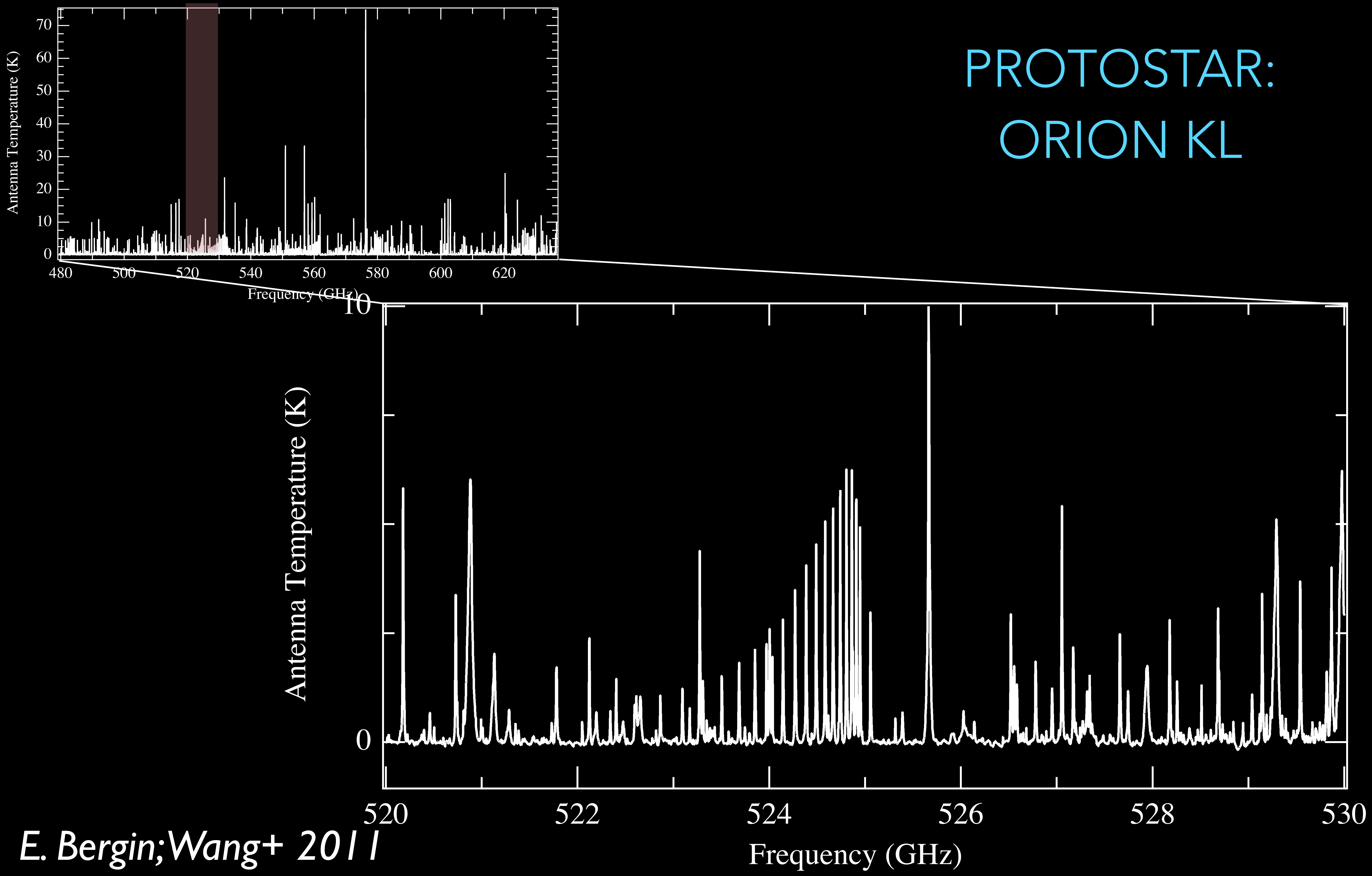
E. Bergin

PROTOSTAR: ORION KL



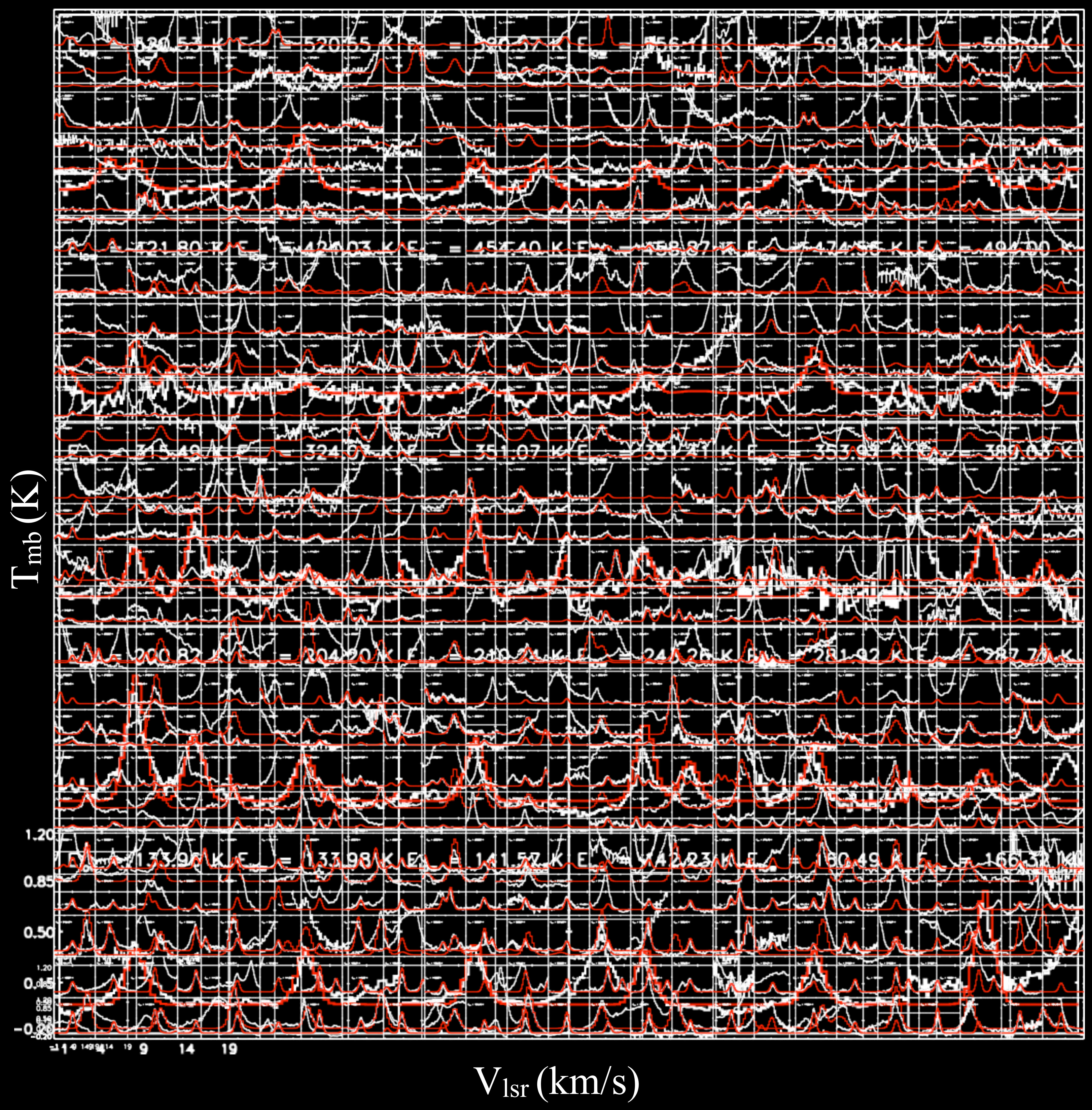
E. Bergin

PROTOSTAR: ORION KL



E. Bergin; Wang+ 2011

EXAMPLE: $HCOOCH_3$



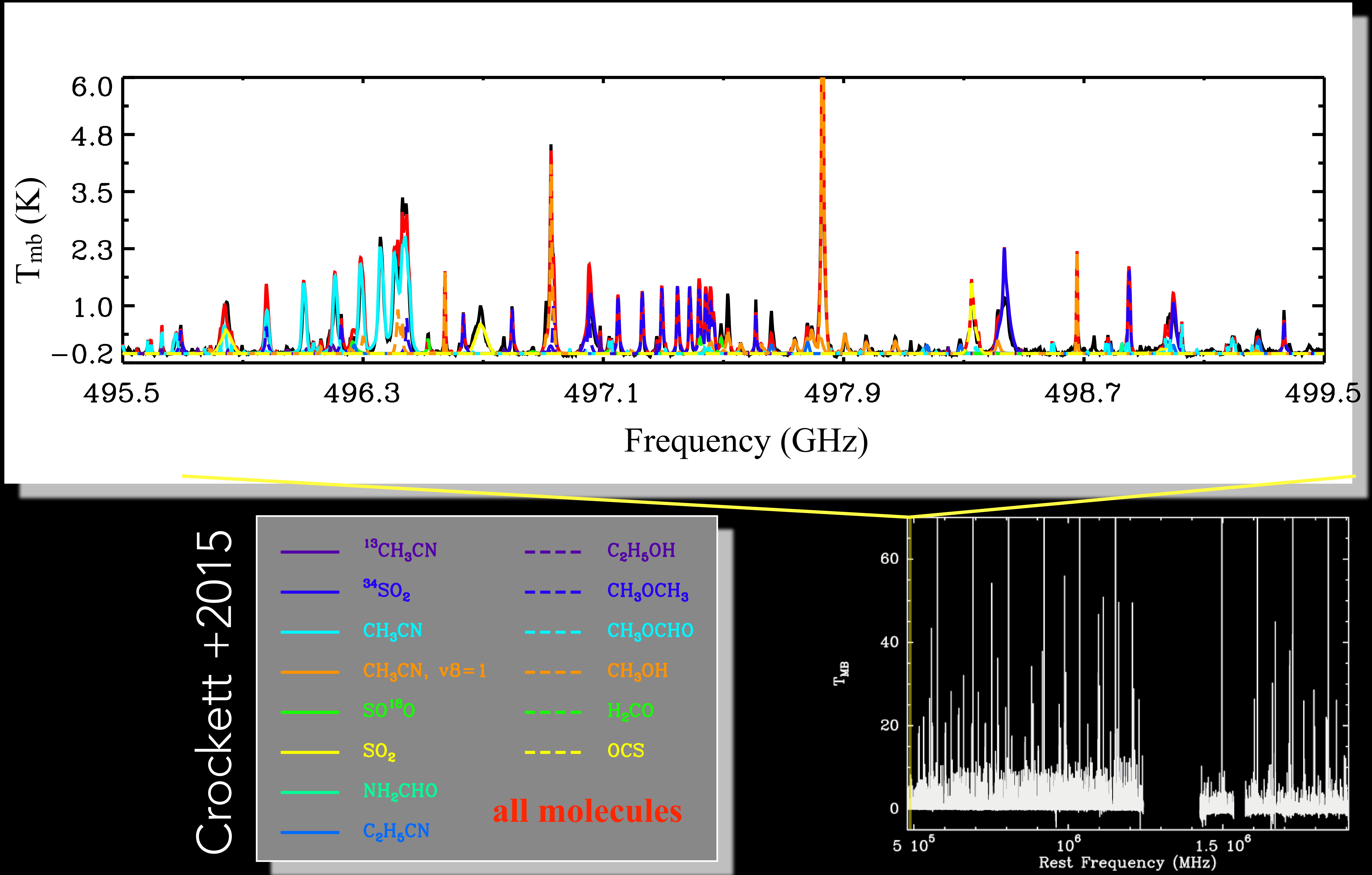
Complex organic with >1000 emissive transitions at HIFI frequencies

Data - plotted in white

LTE Model - single component: $T=110K$, $N_{col}=1x10^{17}cm^{-2}$, $v_{lsr}=8.0$ km/s, $\Delta v=2.5$ km/s

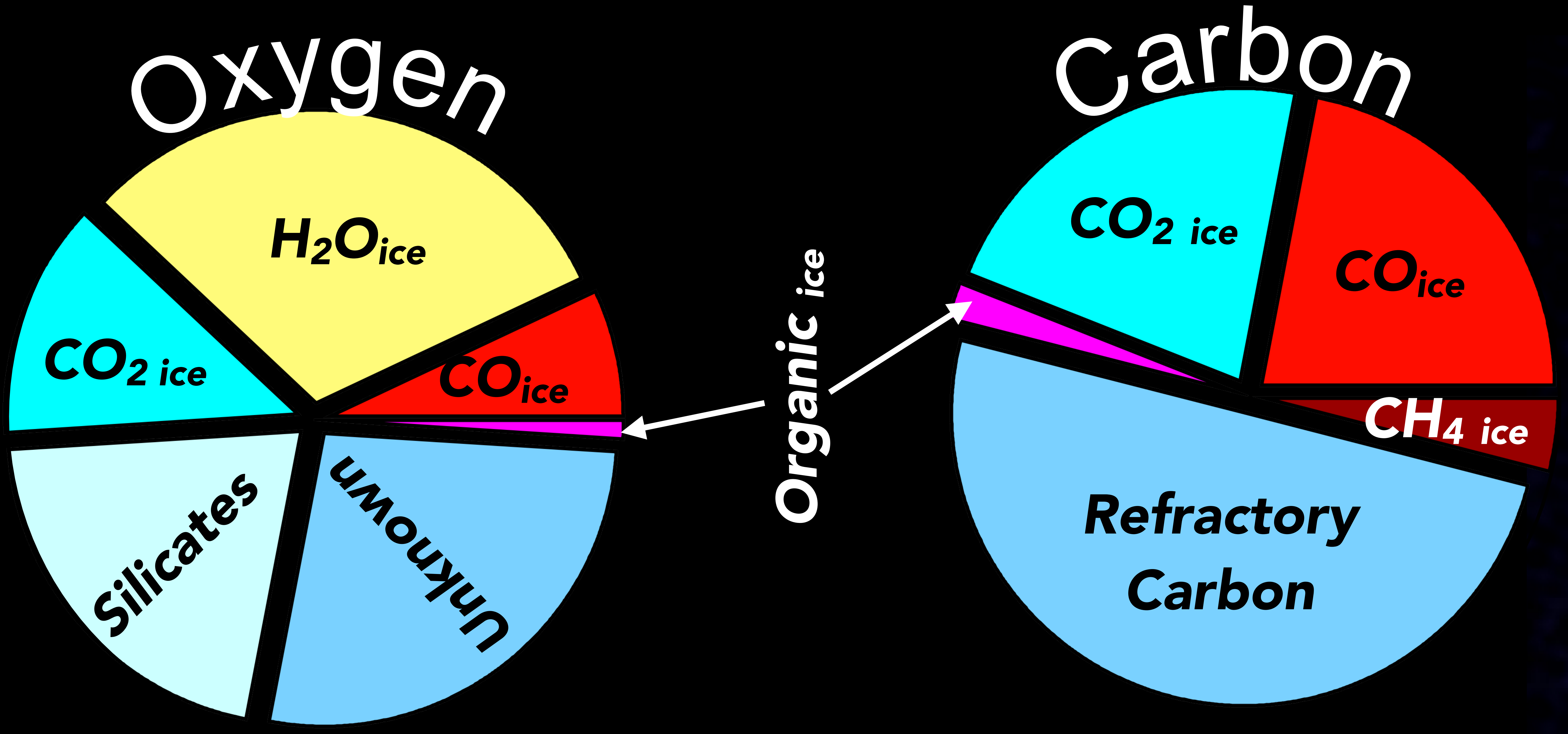
Crockett +2015

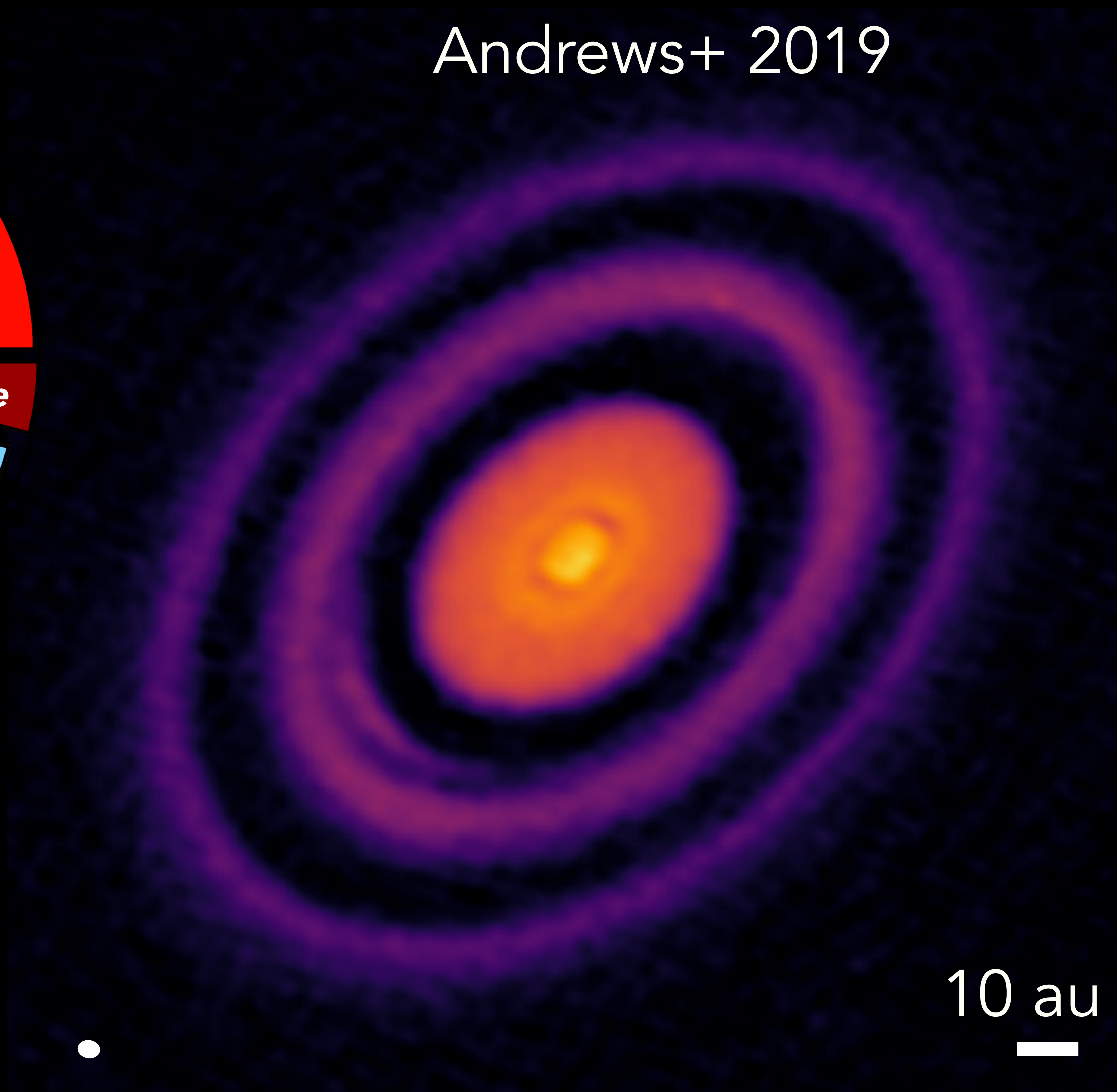
PROTOSTAR: ORION KL



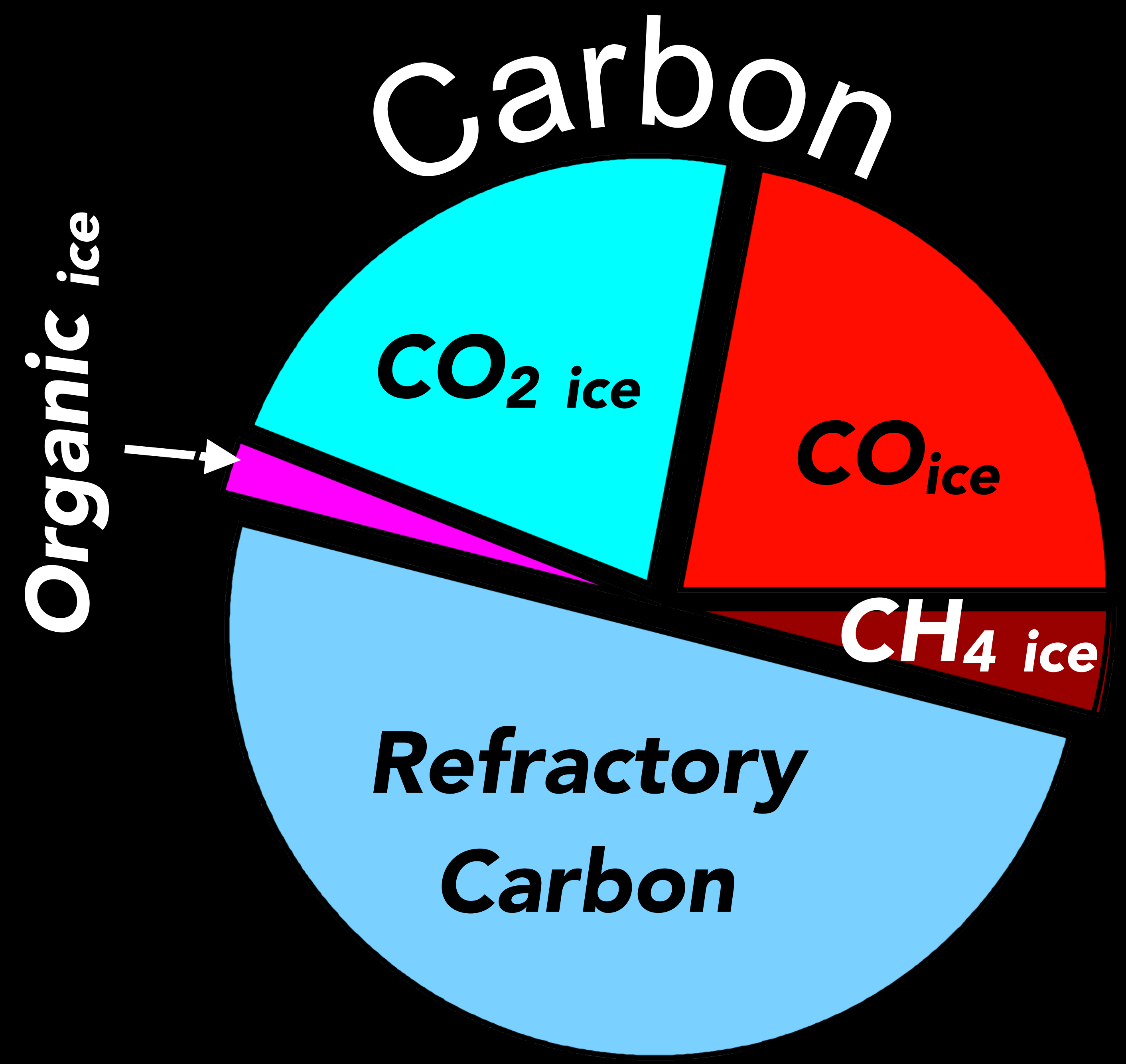
Crockett +2015

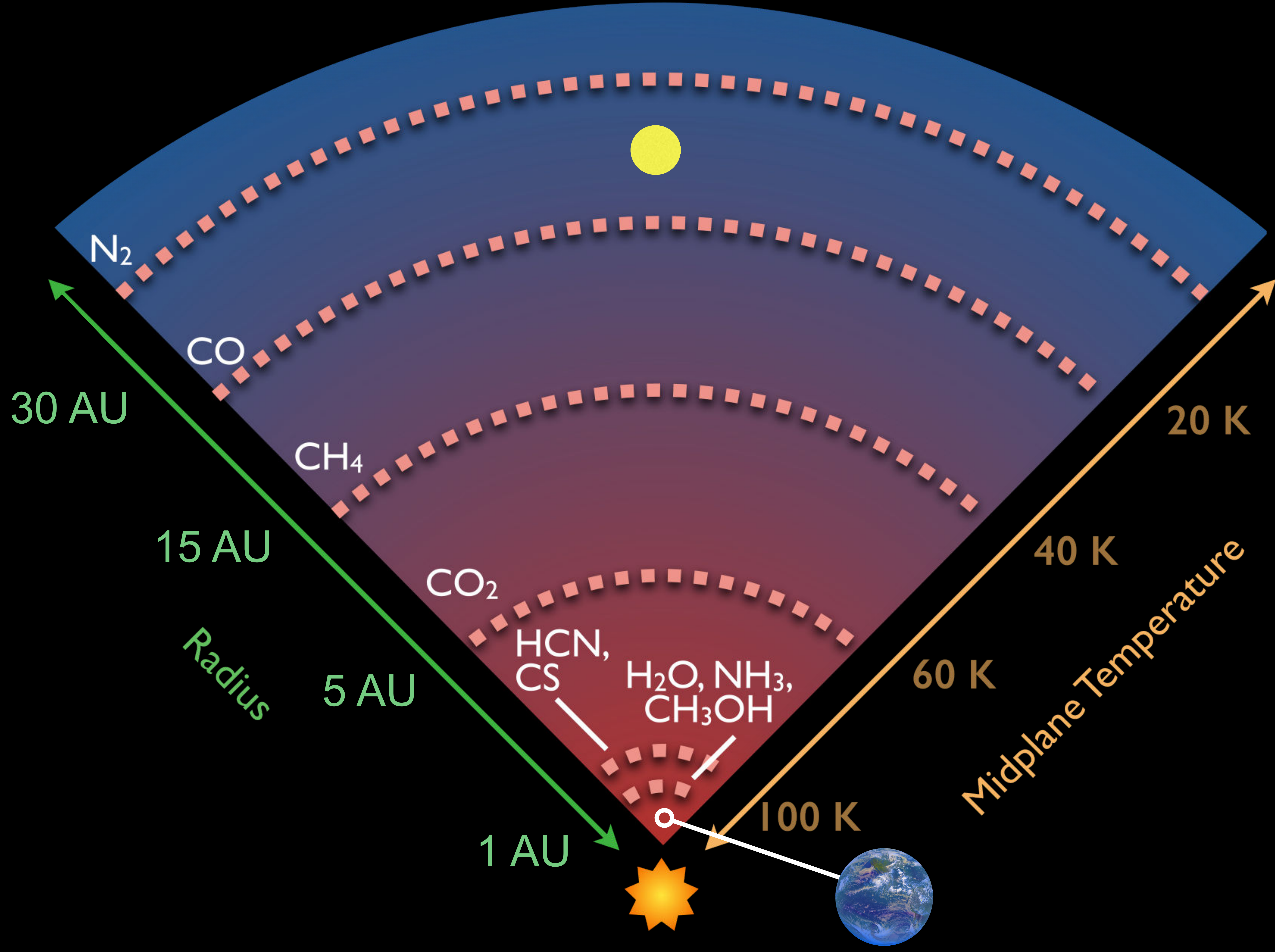
SETTING THE STAGE FOR PLANET FORMATION





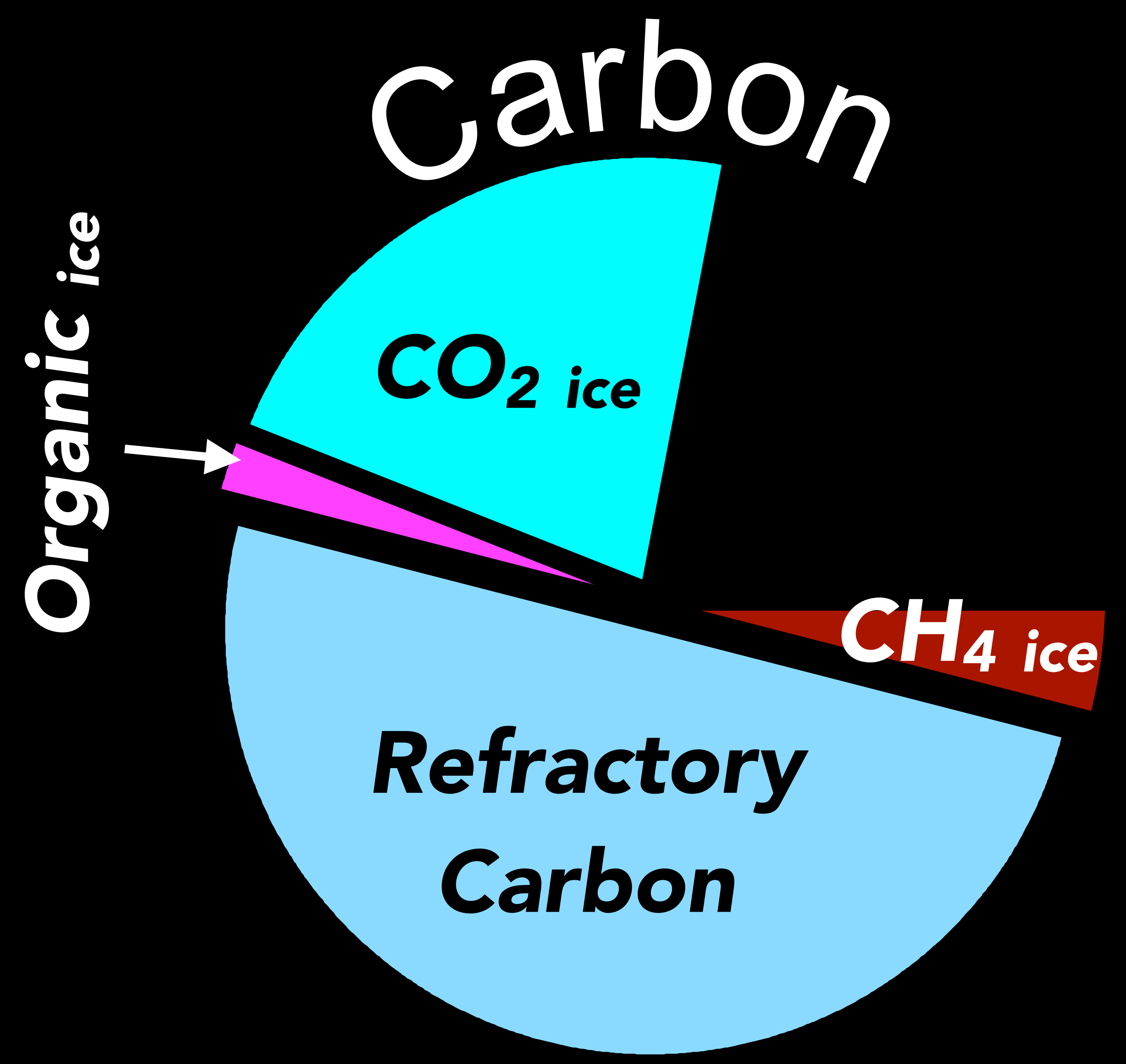
NEPTUNE/URANUS ZONE

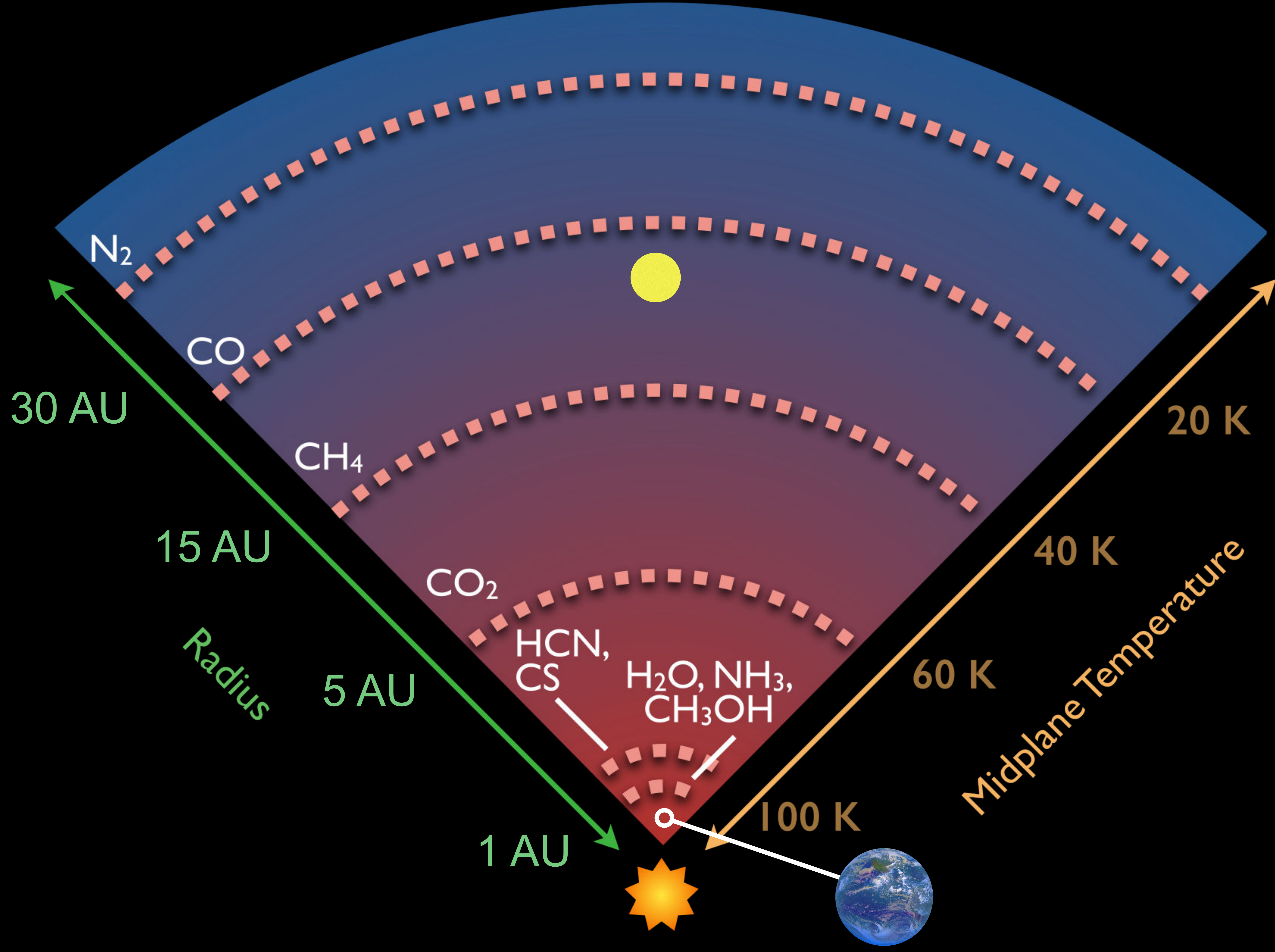




disk structure: I. Cleeves

NEPTUNE/URANUS ZONE





disk structure: I. Cleeves

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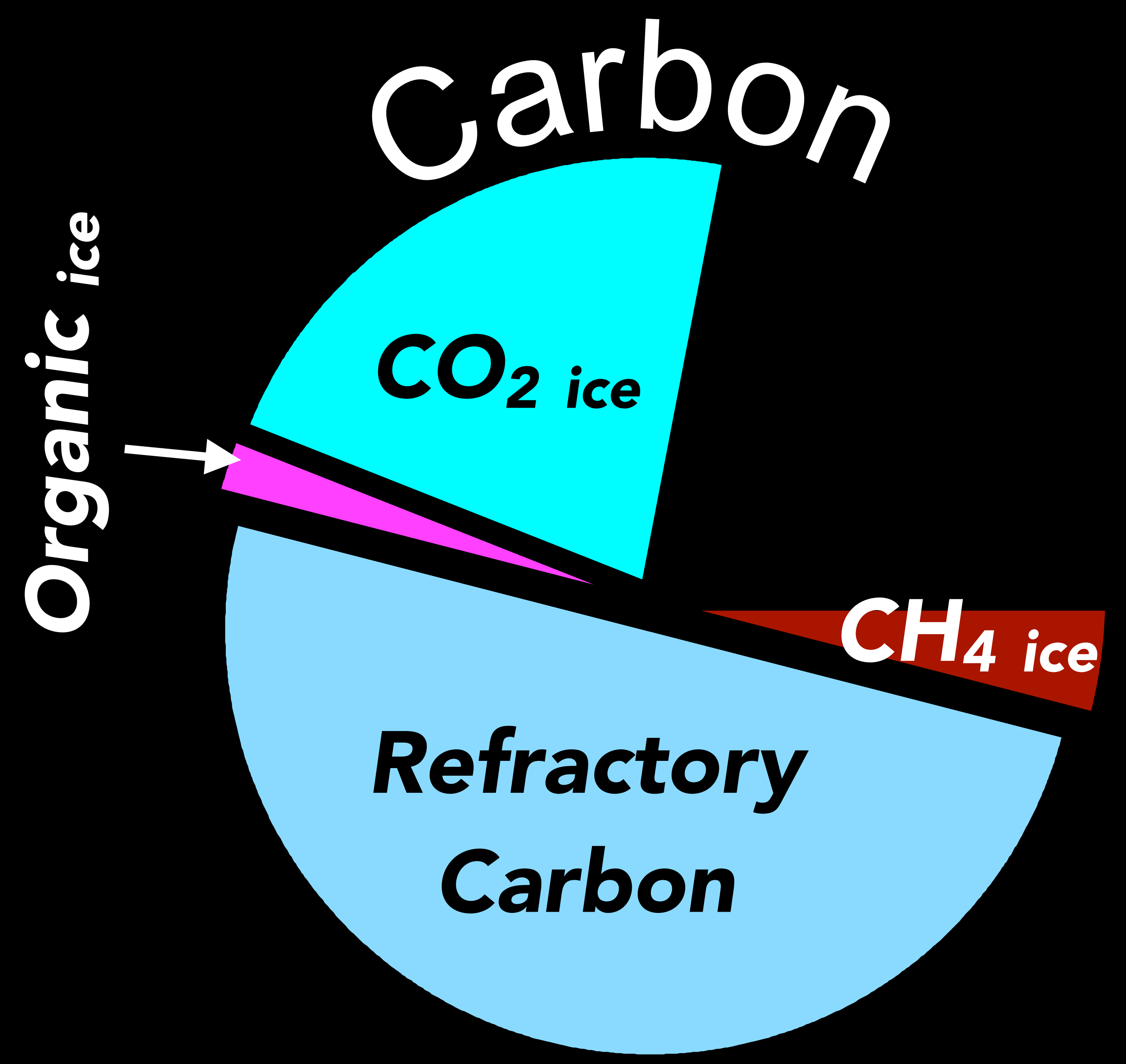
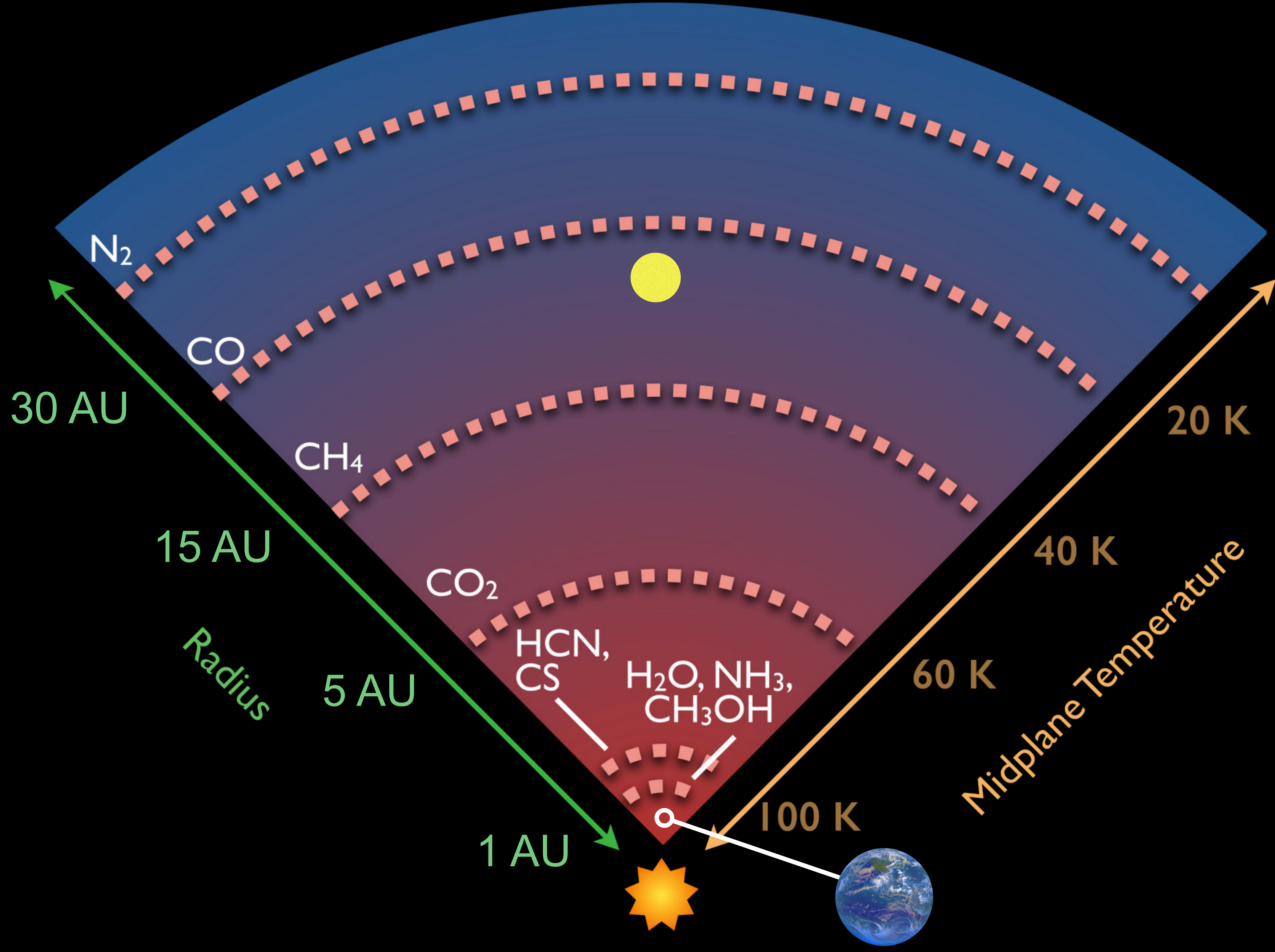
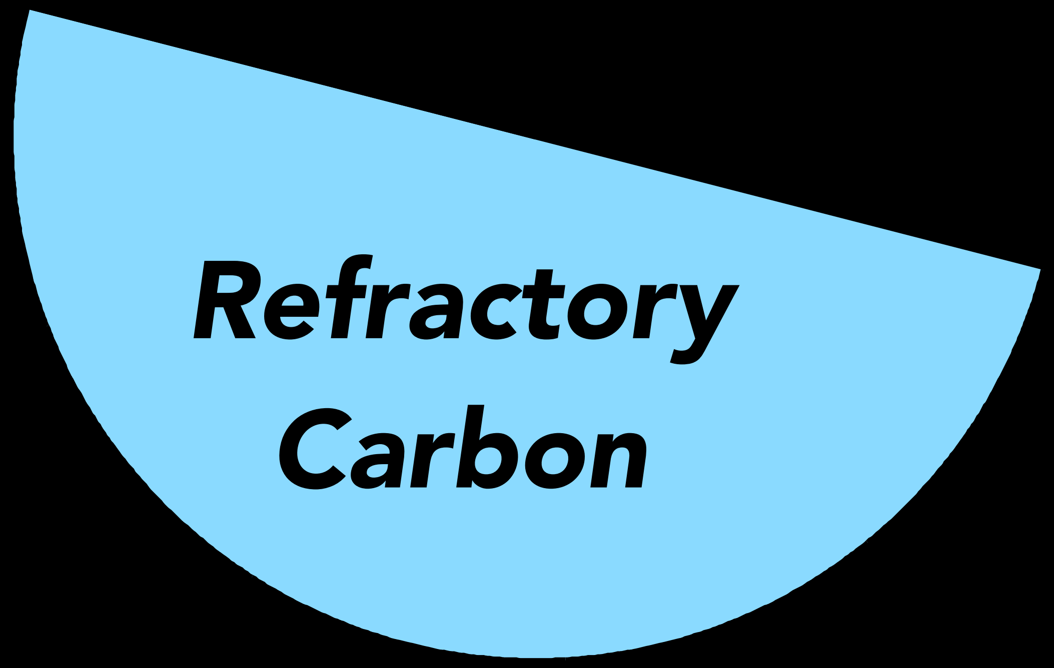


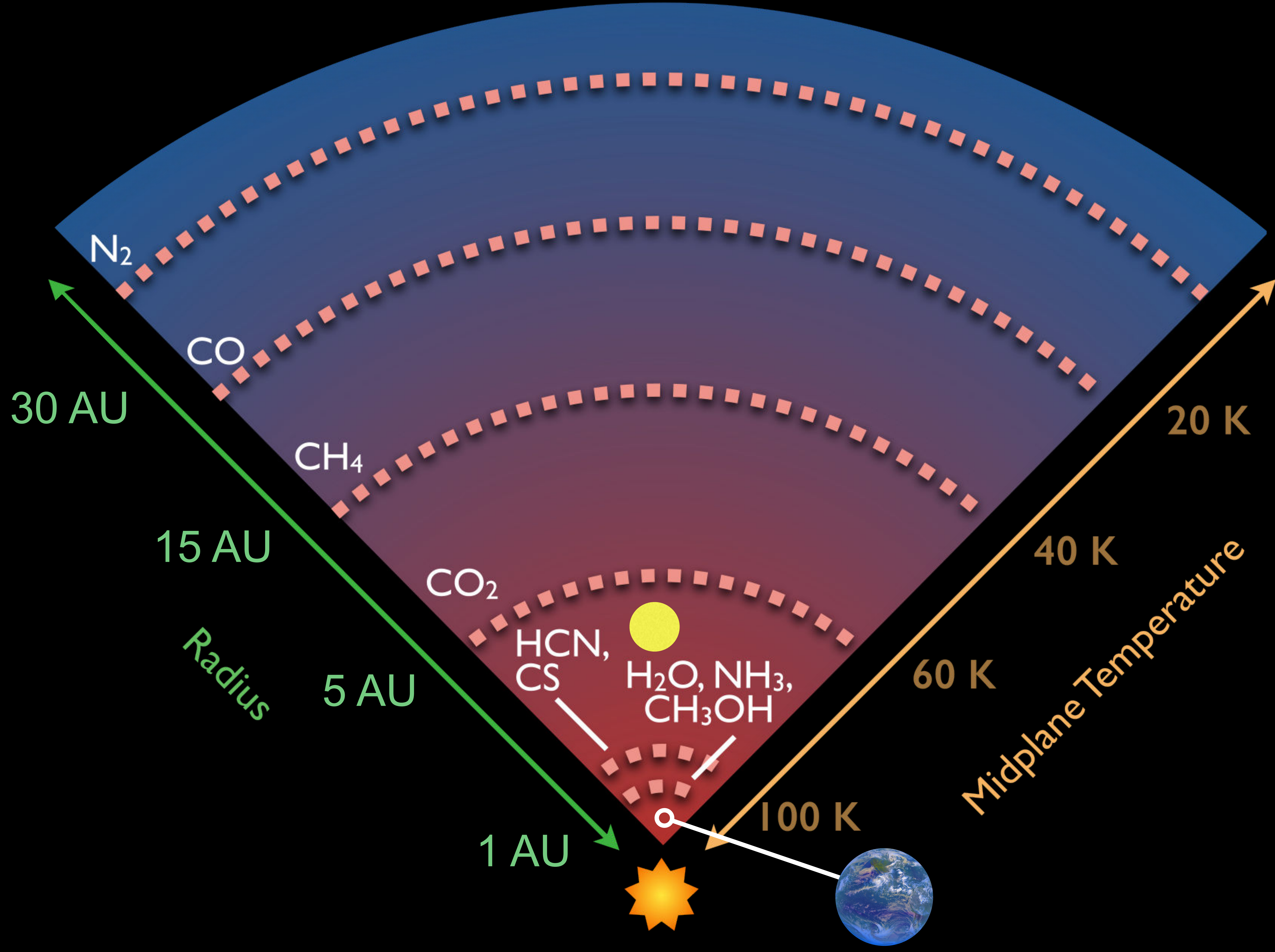


disk structure: I. Cleeves

JOVIAN PLANET ZONE → HABITABLE ZONE

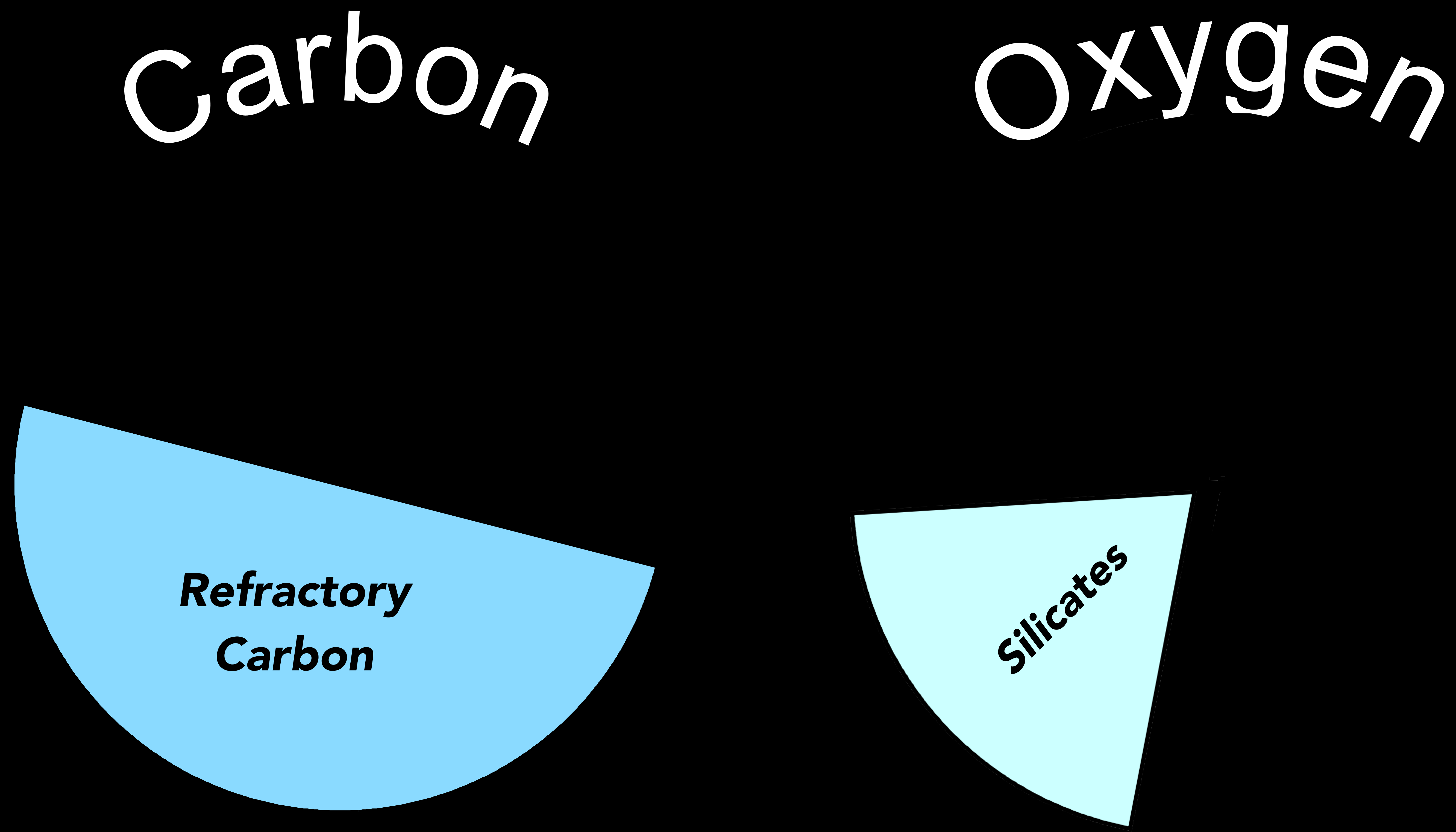
Carbon

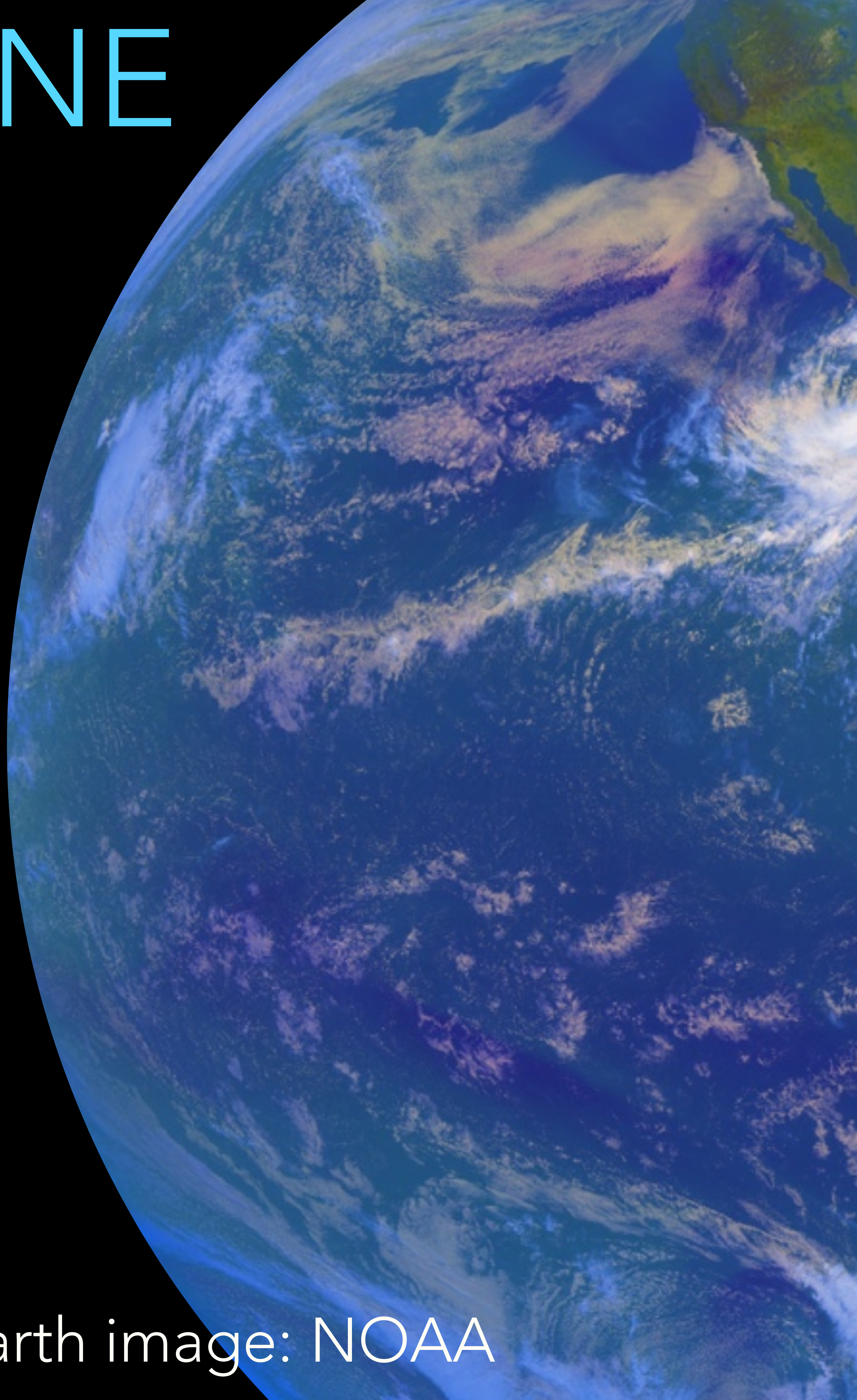




disk structure: I. Cleeves

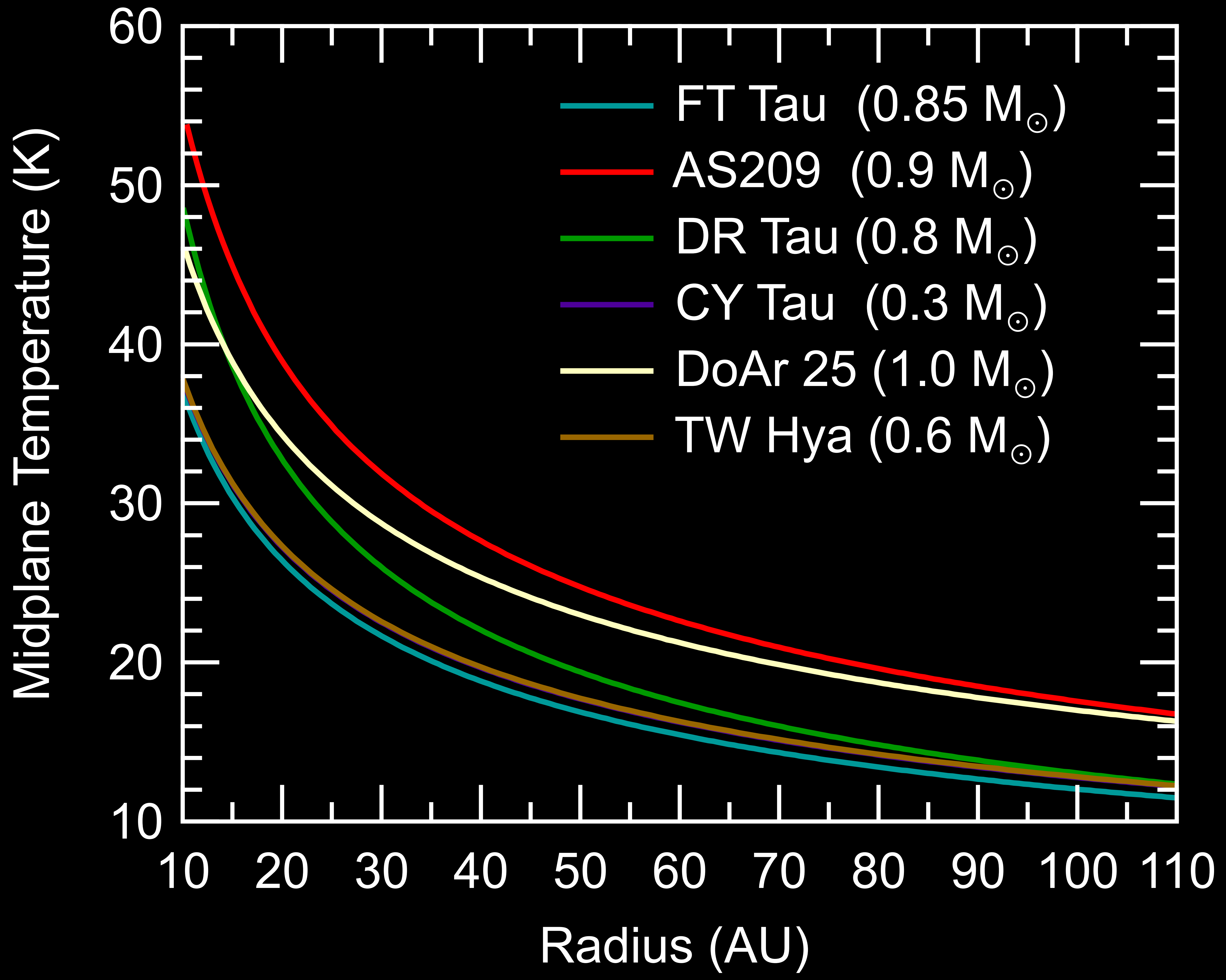
HABITABLE ZONE





Earth image: NOAA

Temperature @ 1 AU - Radiation Dominated



> 1 Myr age for all disks

Long +2018
Andrews+ 2016

Measured temperature of mm-sized grains
<< T_c of refractory carbon carrier

THE HABITABLE ZONE

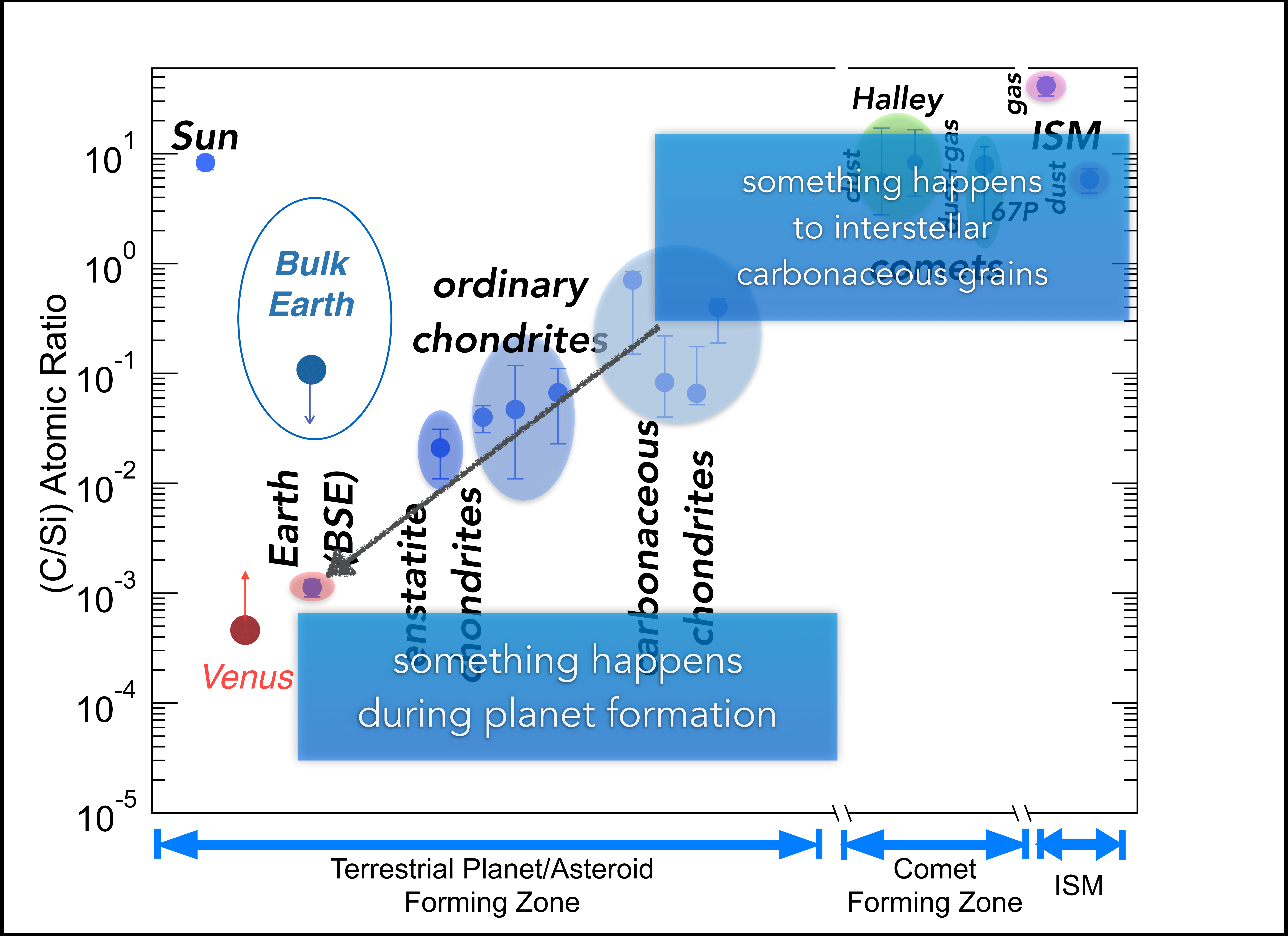
- Problem is the content - look at Carbon to Silicate Ratio in refractory material
- ISM Grain — C/Si ~ 5

➡Silicate Earth - C/Si < 10^{-3}

We should be sitting on a carbon rock with no water!

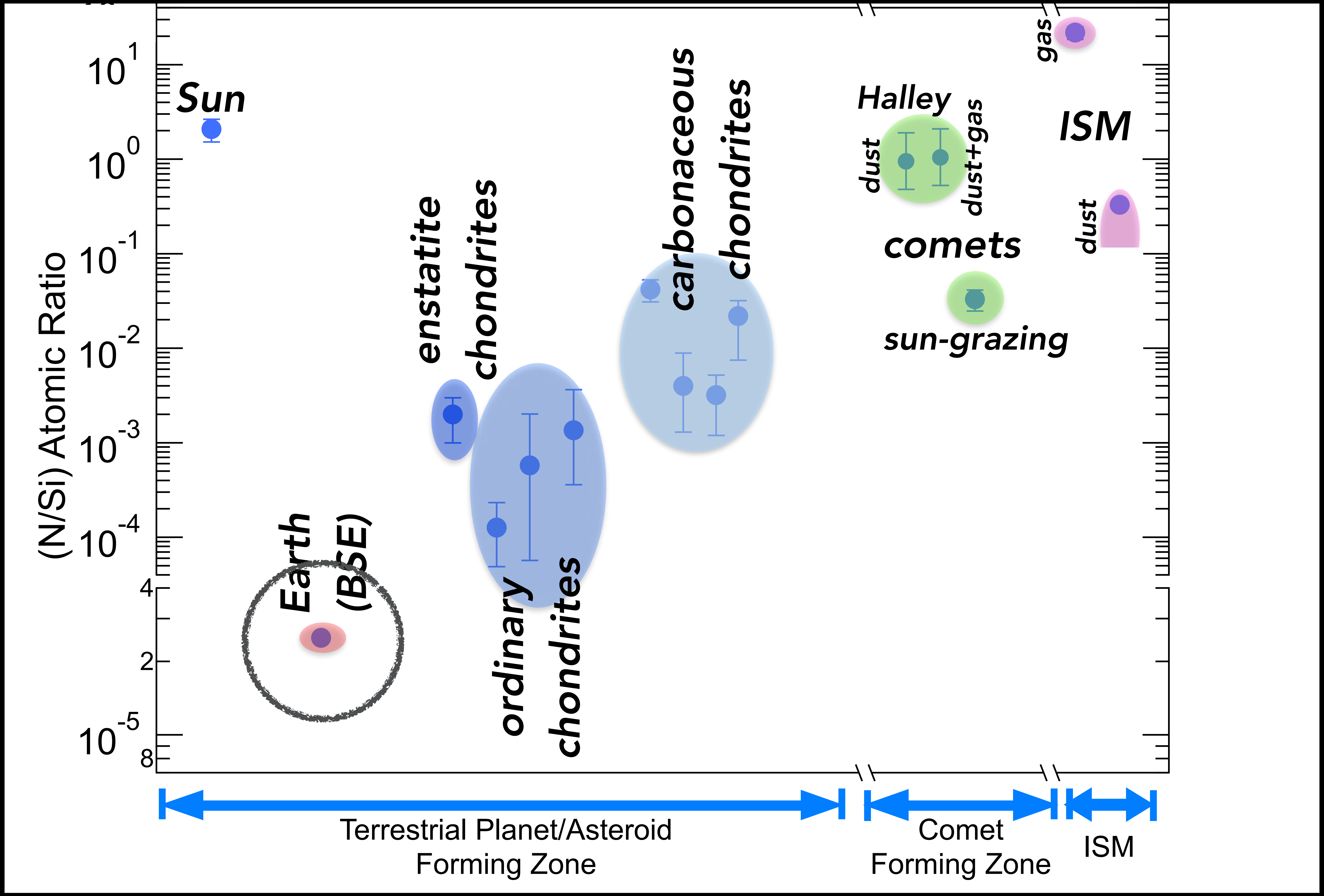
abundances from Lodders 2019; Bergin+ 15; Li+ 2020, in prep.

MAKING AN EARTH?



Bergin +2015; Li+ 2020

Nitrogen


(N/Si) Atomic Ratio
10^1
10^0
10^{-1}
10^{-2}
10^{-3}
10^{-4}
4
2
10^{-5}
8
Sun
Earth (BSE)
enstatite chondrites
ordinary chondrites
carbonaceous chondrites
Halley
dust
dust+gas
comets
sun-grazing
gas
ISM
dust
Terrestrial Planet/Asteroid Forming Zone
Comet Forming Zone
ISM

TERRESTRIAL PLANET FORMATION: Pebbles

ISM C & N RICH GRAIN DESTRUCTION

- In the inner solar system (< 5 au) -
  - Destroy carbon-rich grains
  - Silicates remain intact.
- MUST happen early - before/during planetesimal formation

➡Hard to destroy large rocks

➡Need grains to be small (pebble sized)

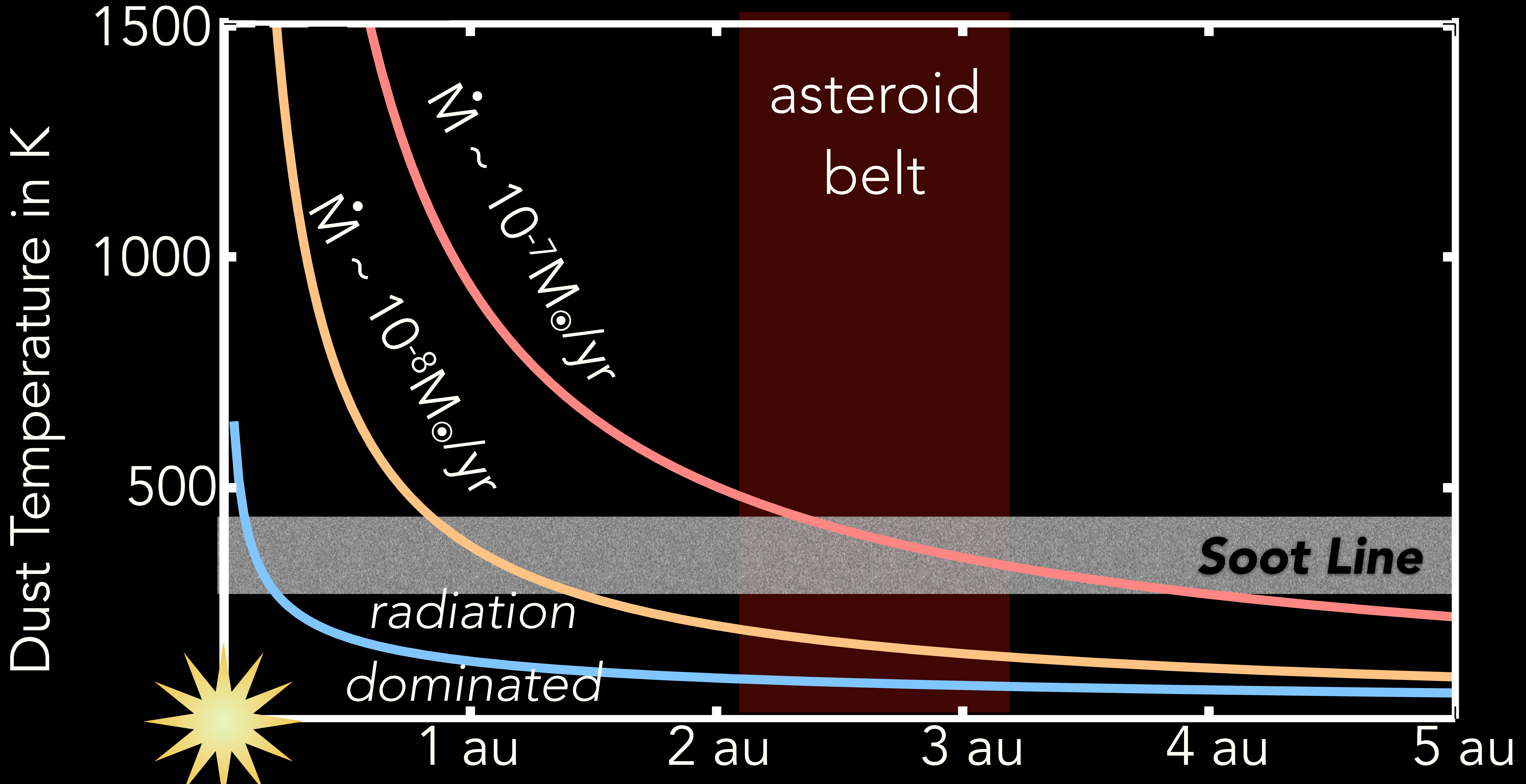
- Release of C and N will have implications for Astrochemistry (Wei et al. 2018; van 't Hoff et al. 2020).

ISM C & N RICH GRAIN DESTRUCTION

Options

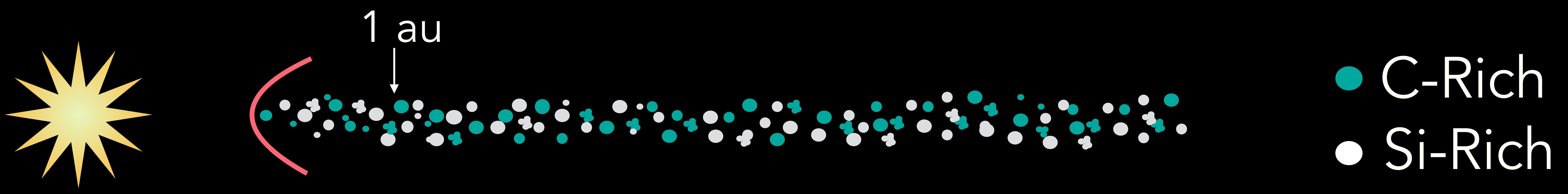
1. **Oxidation** (Lee+ 2005)
   - does not work (Anderson+ 2018; Klarmann+2018)
2. **Sublimation** (Gail & Trieloff 2017; Li+ 2020, in prep.)

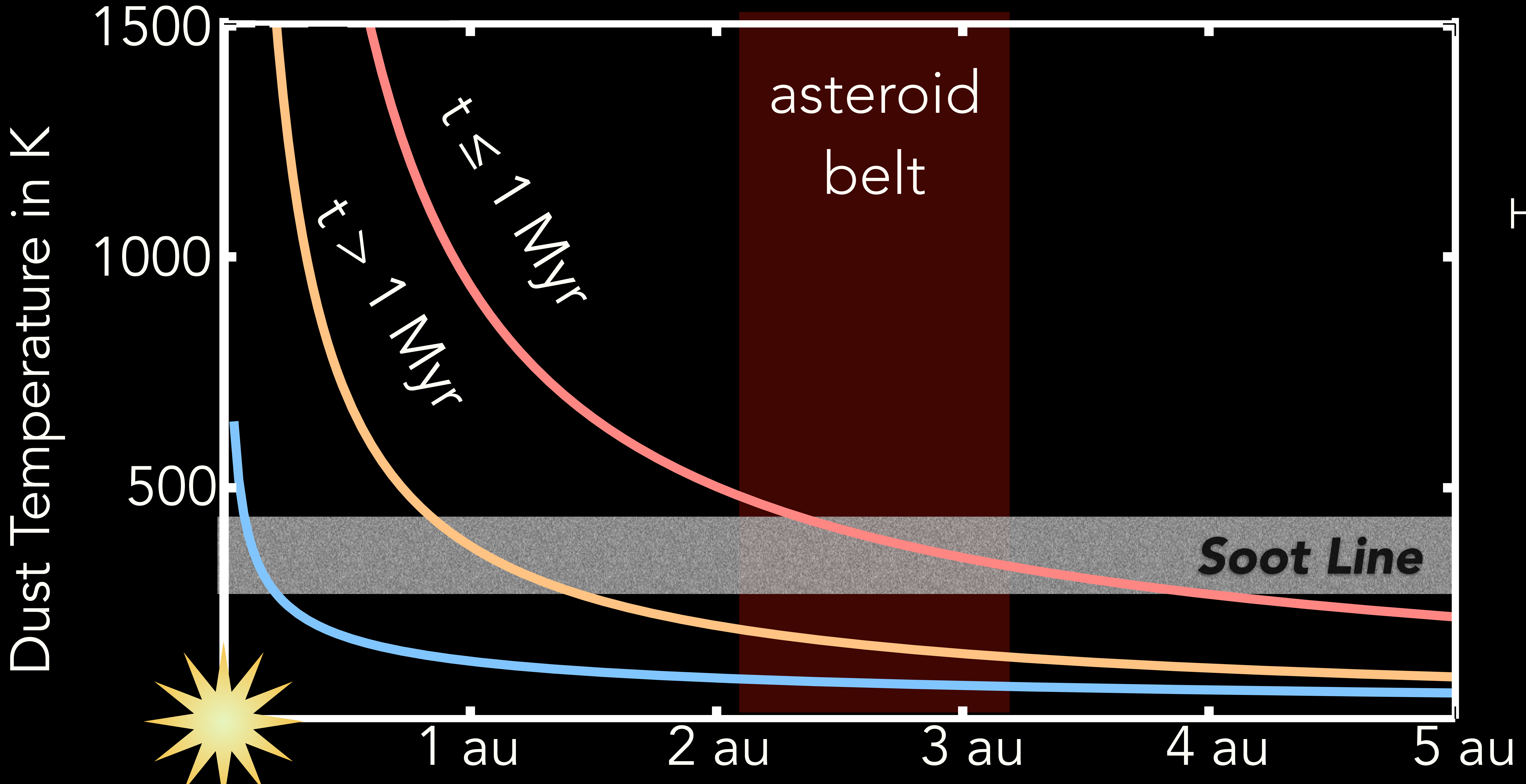
ALTERING EARTH'S BUILDING BLOCKS



Li, Bergin
Blake,
Ciesla, &
Hirschman
2020

ALTERING EARTH'S BUILDING BLOCKS





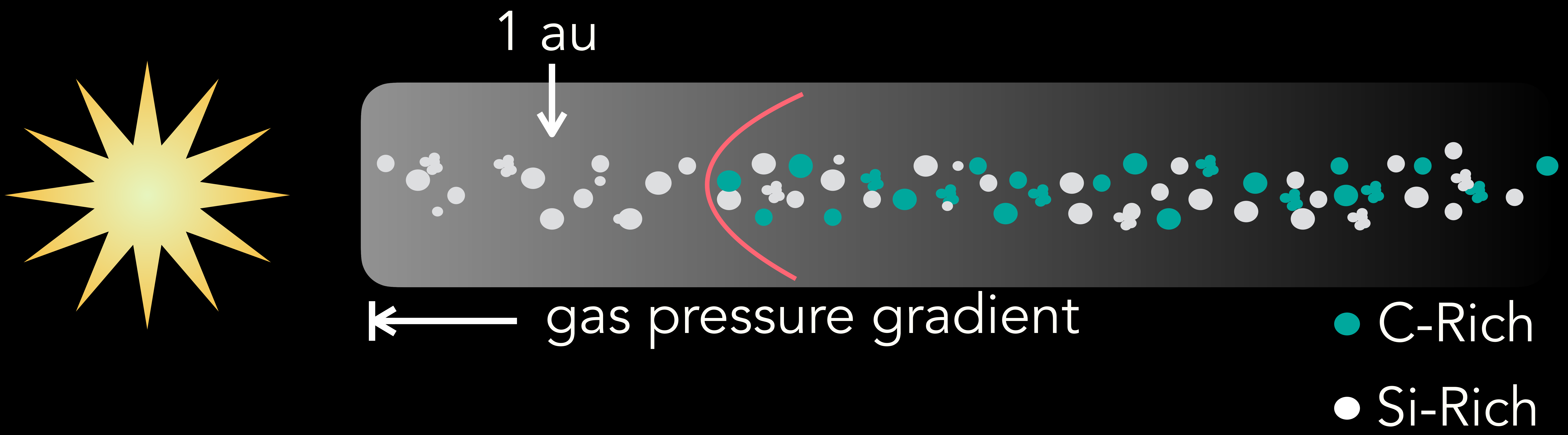
accretion vs time; Hartmann+ 2016

Li, Bergin Blake, Ciesla, & Hirschman 2020

EARTH'S BUILDING BLOCKS

- complication:

➡C & N rich pebbles drift inwards providing continuous supply of carbon to 1 AU



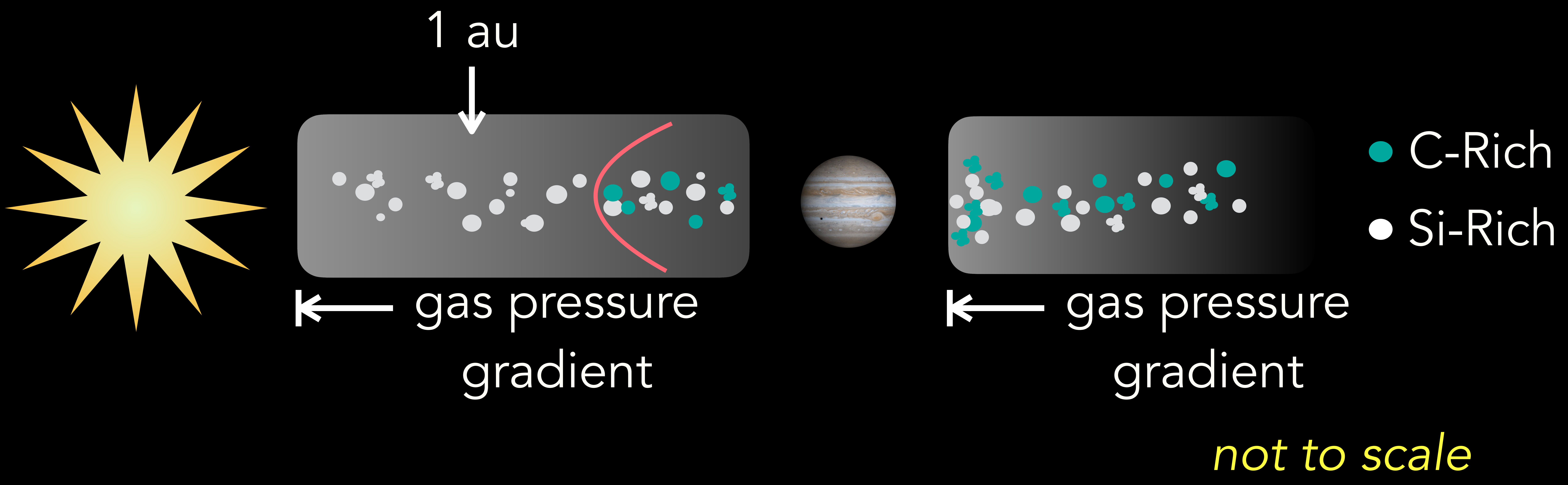
not to scale

EARTH'S BUILDING BLOCKS

- possible solution:

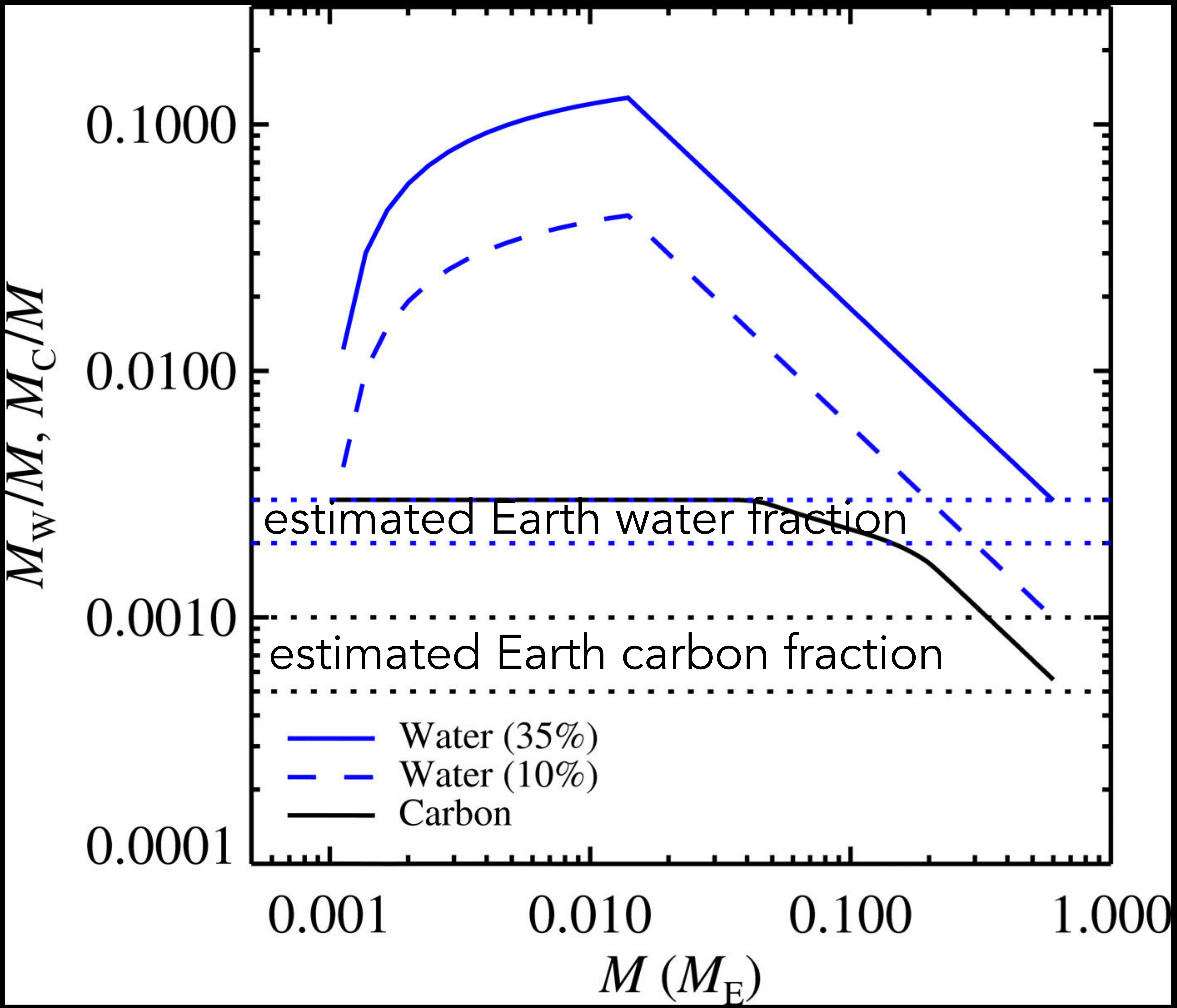
➡ *Jupiter core formation by ~1 Myr (Kruijer+ 17)*

➡ *Earth's building blocks have modest amounts of C and N with (possibly) some water*



PEBBLE ACCRETION LOSS TERMS

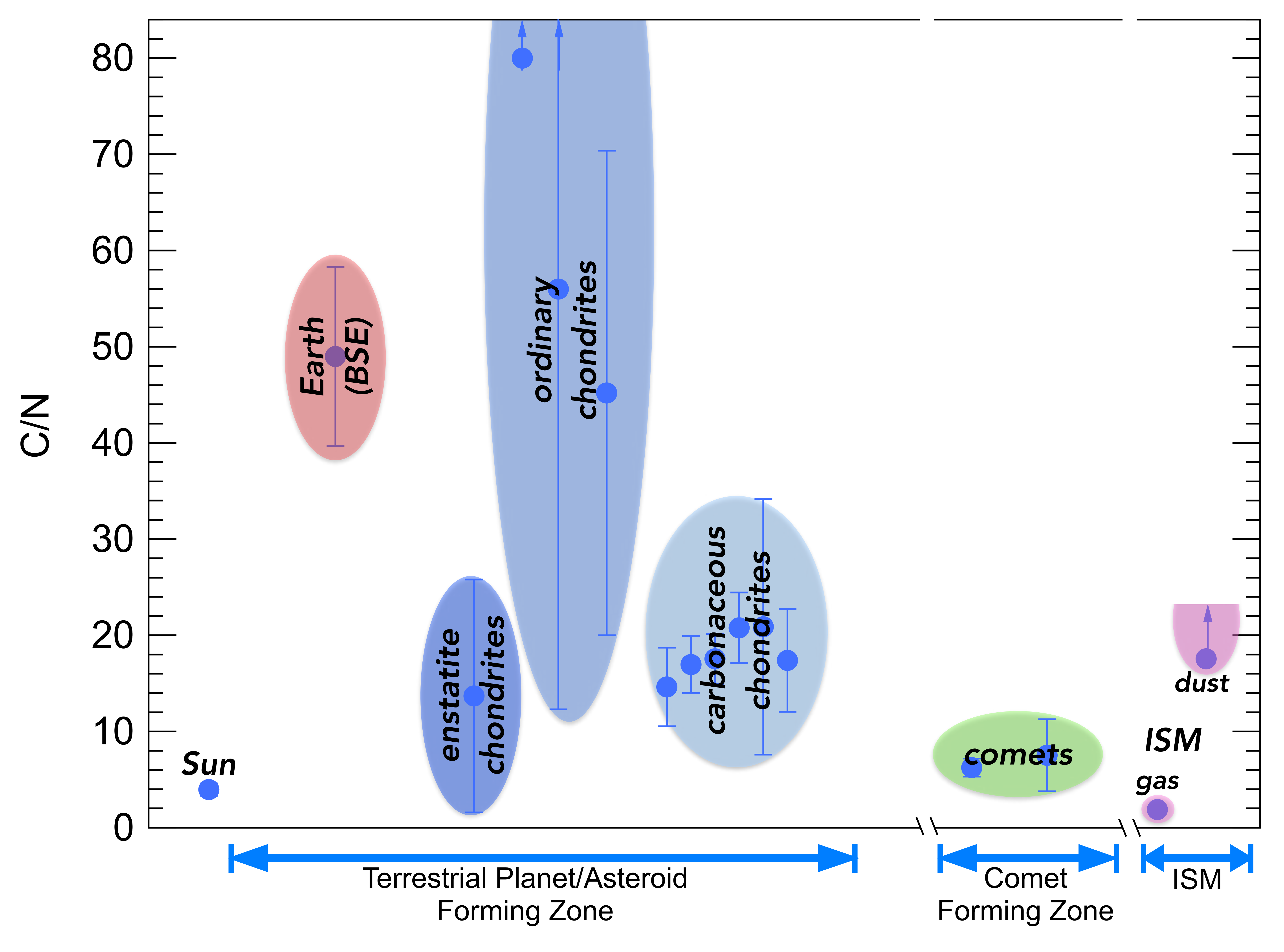
- ➡ Modeled pebble accretion of a proto-Earth forming inside the ice line.
- ➡ Growing planet attracts gaseous envelope heated by pebble accretion luminosity.
- ➡ At some point becomes hot enough to sublimate water and refractory carbon - this is lost.
- ➡ In their model volatile fraction comes from material accreted early prior to sublimation.



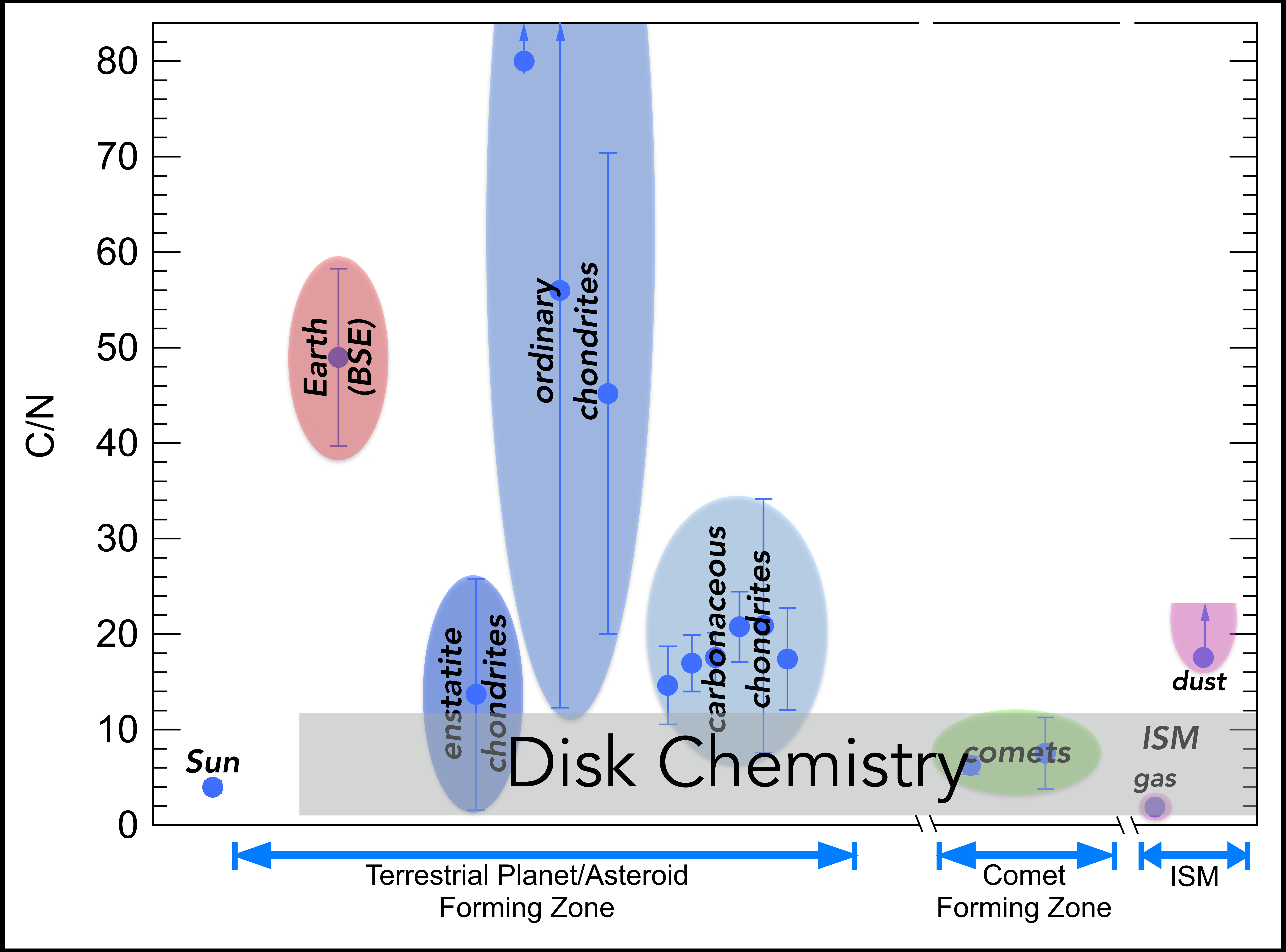
Johansen et al. 2021

TERRESTRIAL PLANET FORMATION: Planetesimals

C/N as a Tracer of Process

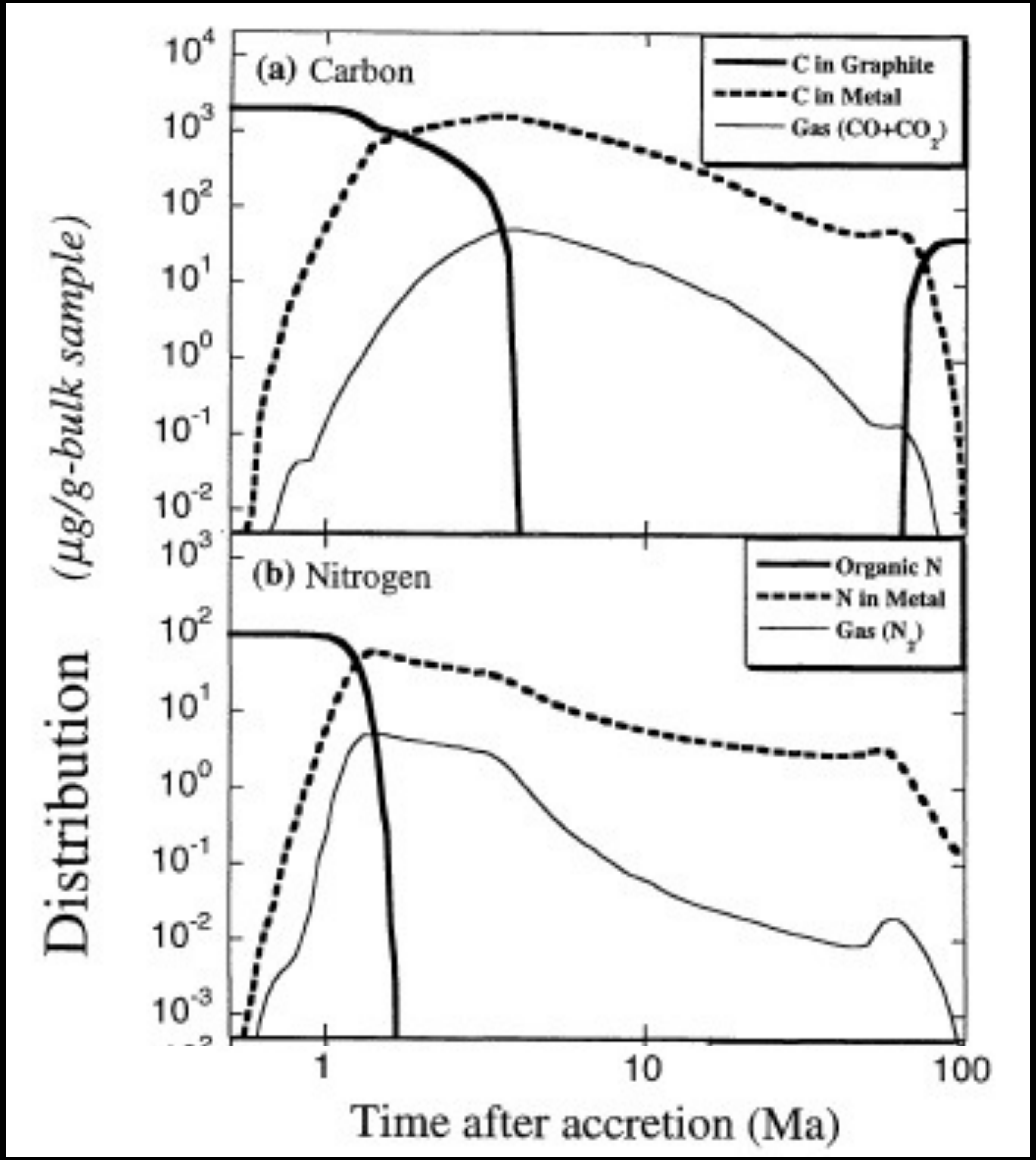


C/N as a Tracer of Process



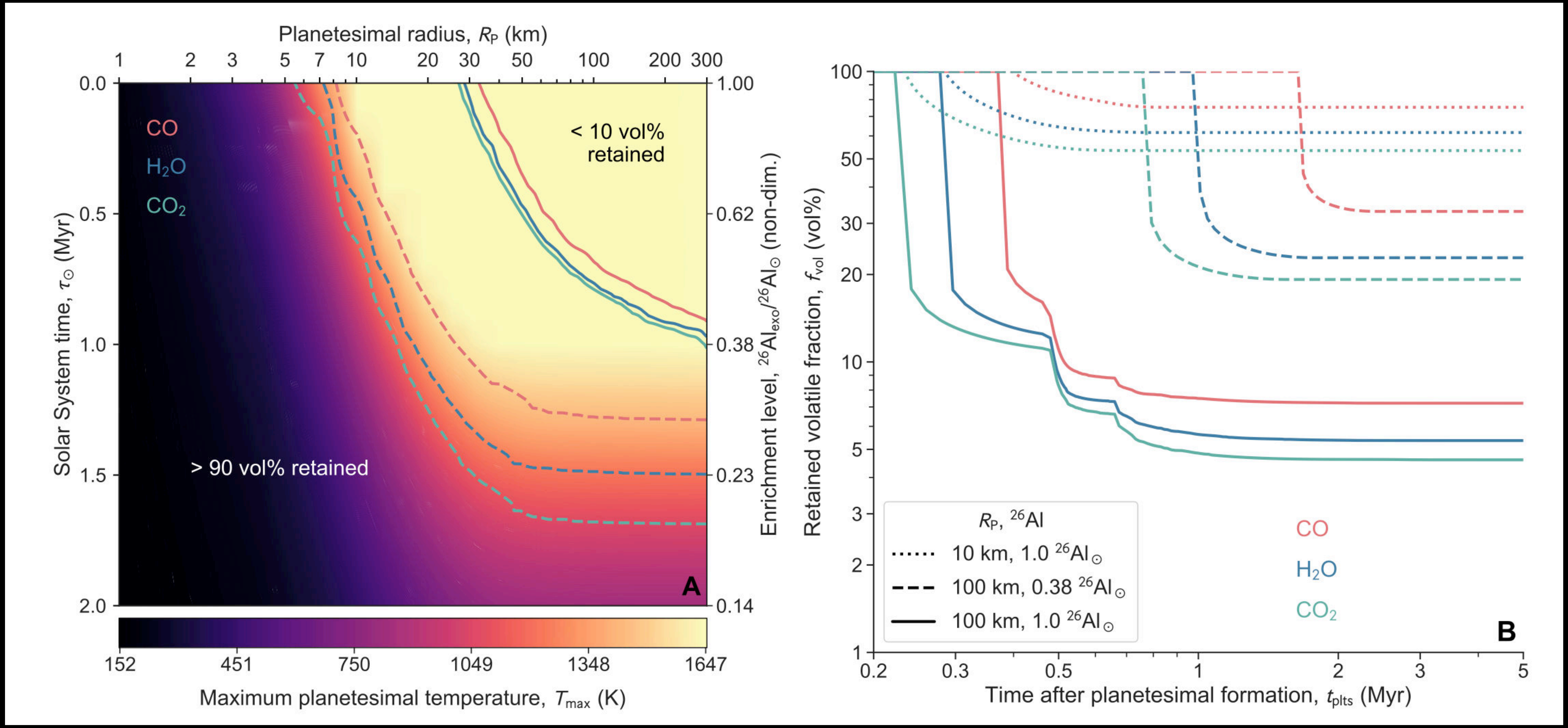
Parent Body Processing: Hashizume & Sugiura 1998

- ➡ ordinary chondrites: exposed to vary degrees of thermal metamorphism
- ➡ T can reach 1300 K in center of 40 km sized body
- ➡ depending on oxidation state can decompose organics and devolatilize C and N



Hashizume & Sugiura 1998

Parent Body Processing: Lichtenberg & Krijt 2021



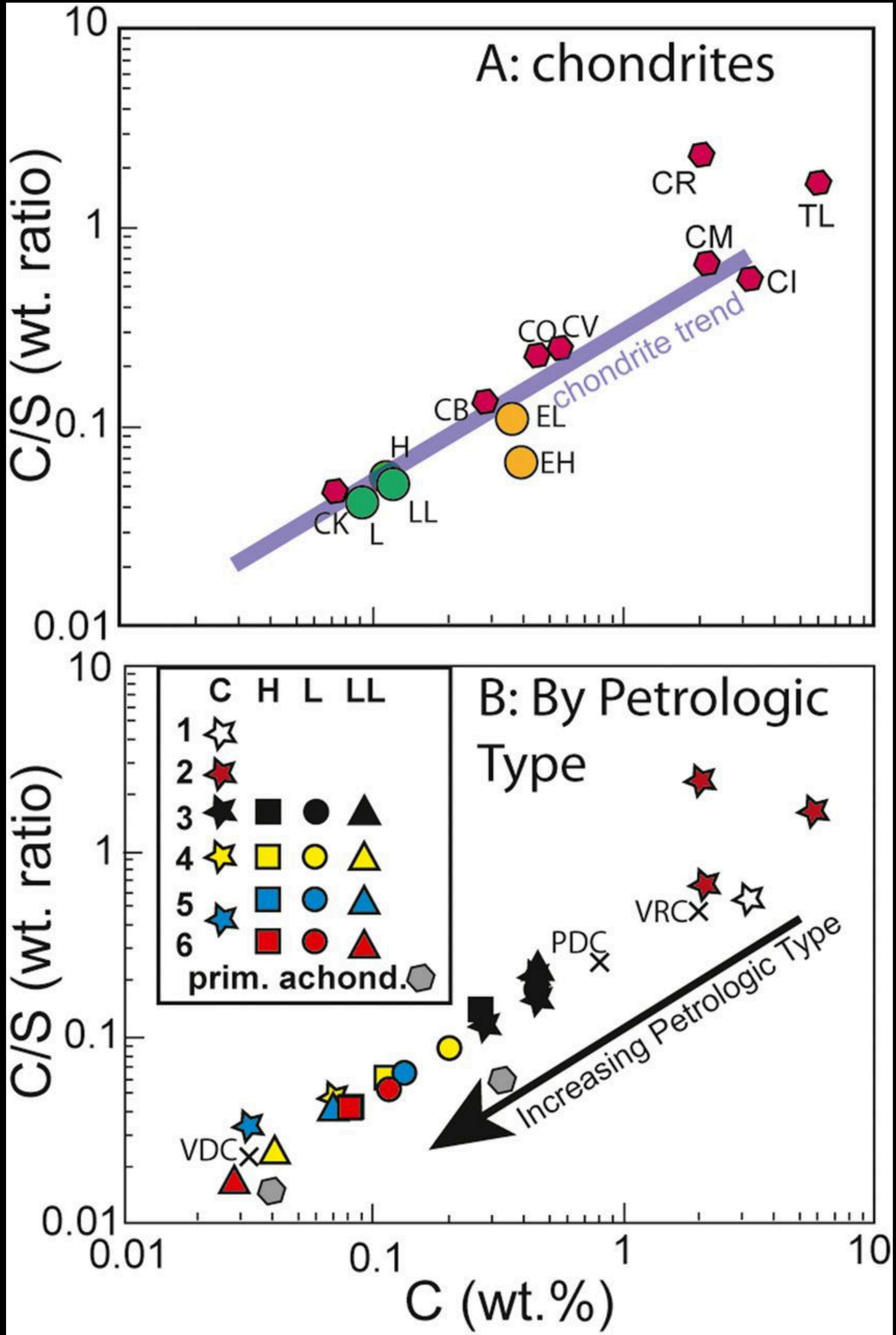
➡ Combined chemistry (CO processing) and planetesimal evolution.

➡ Potential for significant volatile loss due to ^{26}Al heating.

➡ When a planetismal forms matters….

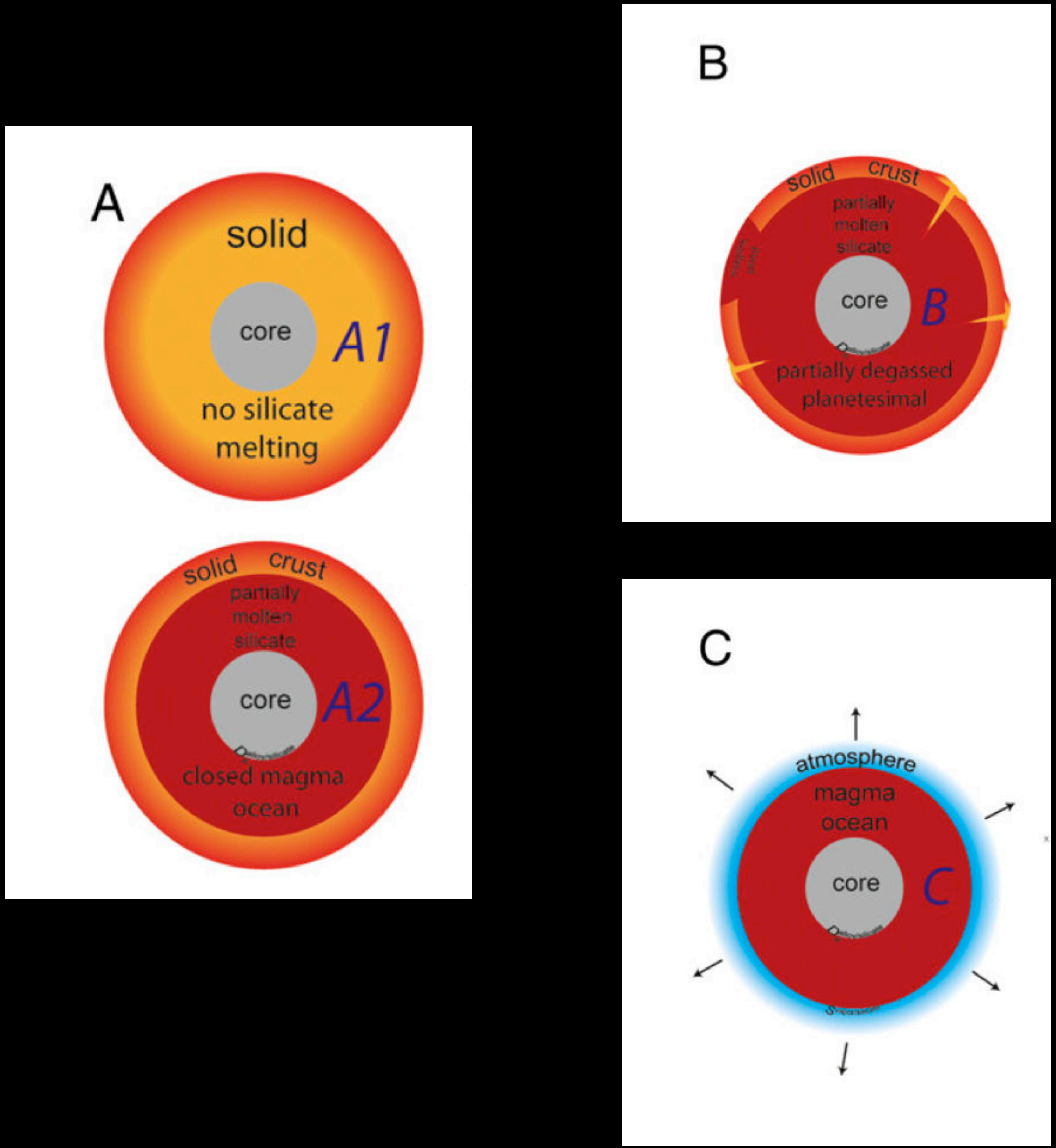
Parent Body Processing: Hirschmann et al. 2021

- ➡ Looked at relative C/S concentrations in iron meteorites.
- ➡ Given the expectation that carbon is in the Earth's core it is likely if carbon was in the parent bodies it should have been carried to their cores.
- ➡ Are these bodies truly carbon-poor (i.e. primordial gradient) or is there loss?
- ➡ Demonstrated tha parents bodies must have had higher C content, but were still "carbon-poor".



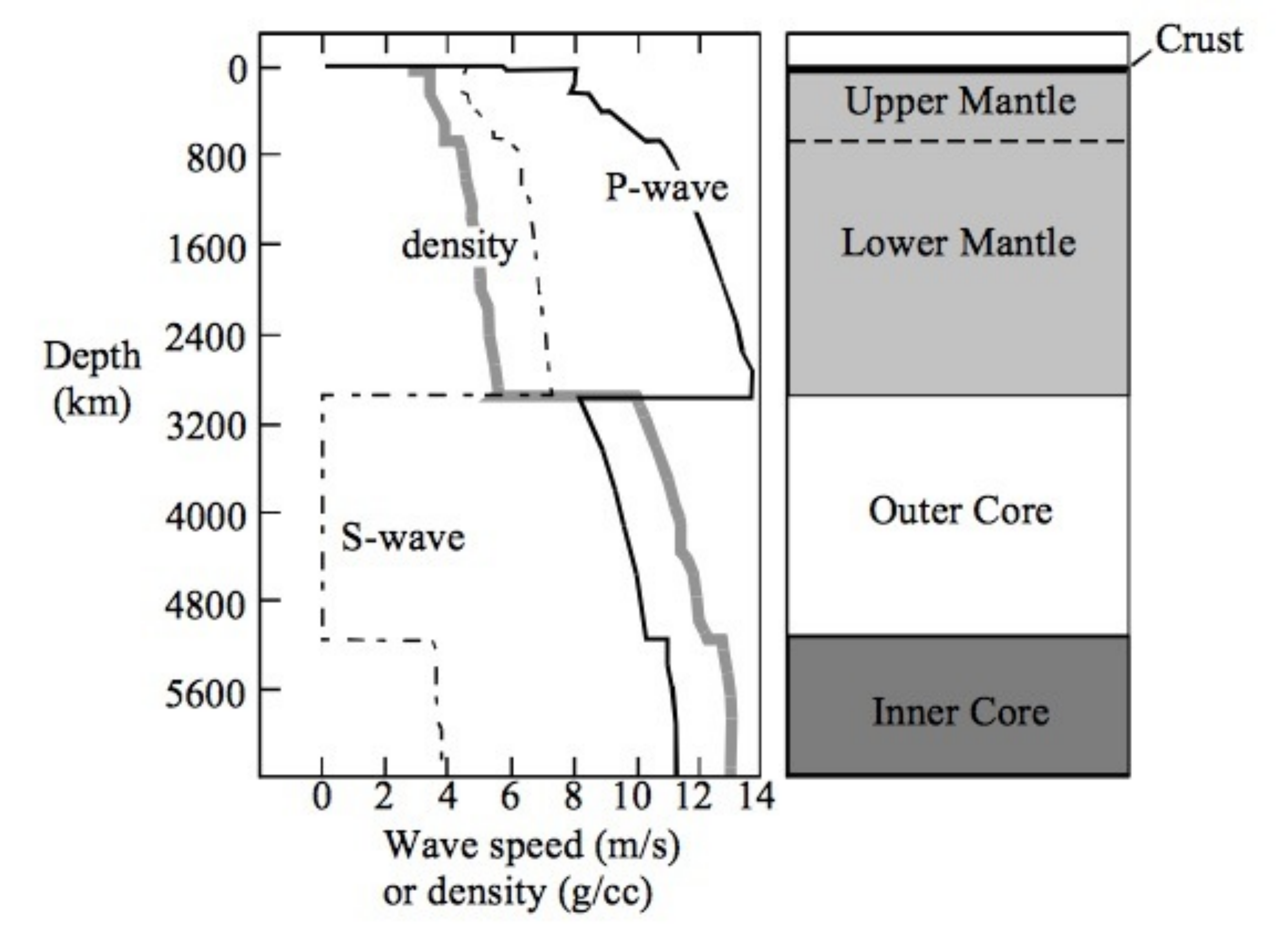
Parent Body Processing: Hirschmann et al. 2021

- ➡ Looked at relative C/S concentrations in iron meteorites.
- ➡ Modeled closed systems and ones where outgassing occurred.
- ➡ Key facet is solubility. S is more soluble than C in silicate melts (i.e. will have less loss).
- ➡ C/S ratios require significant C loss in parent bodies of iron meteorites.



TERRESTRIAL PLANET FORMATION: Magma Oceans

Light Elements in Earth's Core

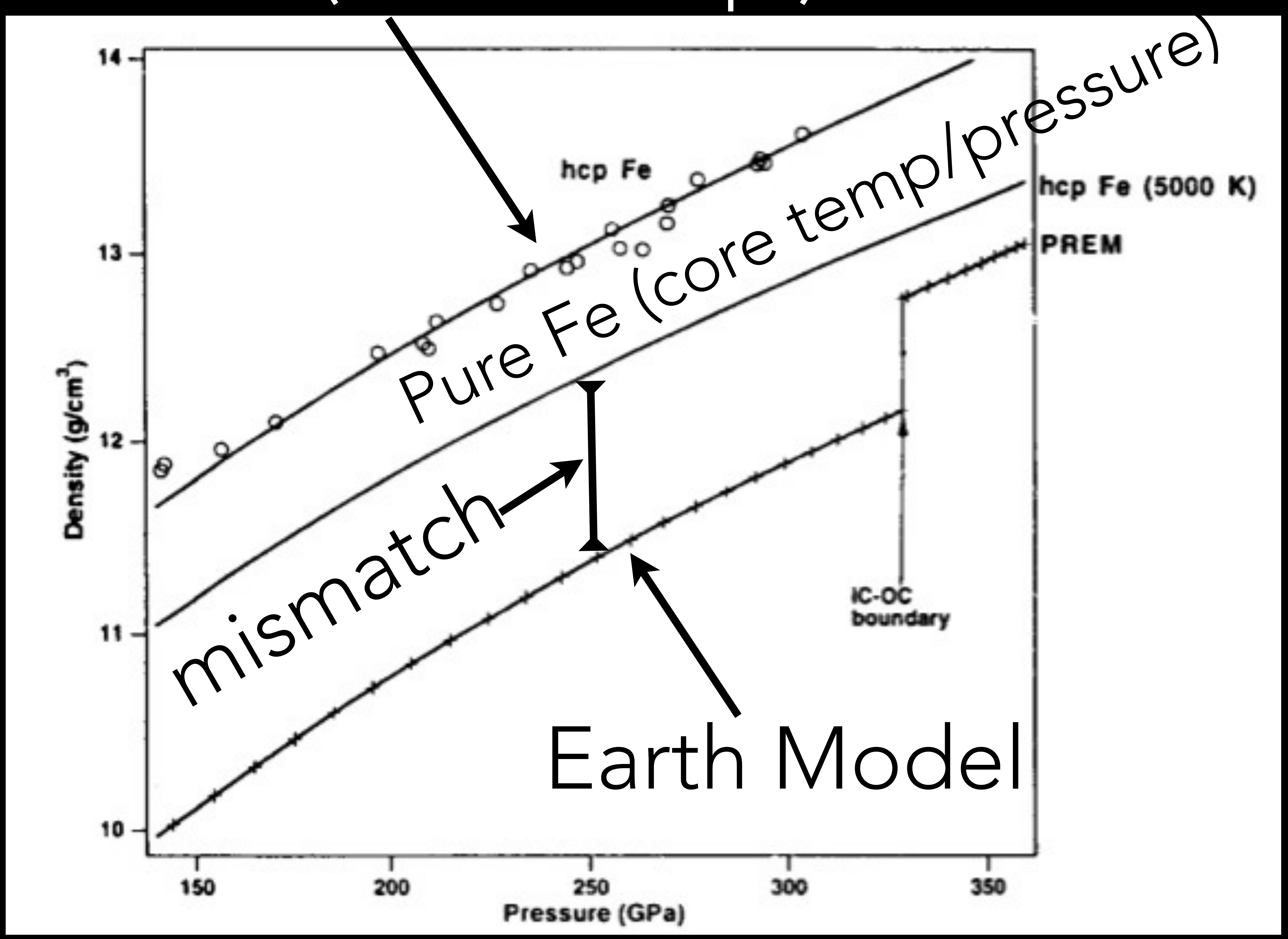


McDonough 1999

➡ can measure the density of Earth's interior via propagation of seismic waves

Light Elements in Earth's Core

Pure Fe (room temp.)



Poirier 1994; Birsch 1952

- ➡ lower than expected density (than Fe) based on seismic wave propagation
- ➡ potential elements: H, C, O, Si, S, N


MAGMA OCEAN

Key Factors: C/N & Core Formation

- Solubility in silicate melt

➡ C more soluble than N - oxidizing conditions

➡ N more soluble than C - reducing conditions

Oxidized vs Reduced

- Standard definition - loss (oxidized) or gain (reduced) of an electron.
- H is a reducing agent, O is a oxidizing agent
- Scenarios:
  - ➡ Planetary embryos potentially existed as early as 2 Myr after CAI's (Dauphas and Pourmand 2011).
  - ➡ Gas-rich nebula was present.
  - ➡ Early H_2 atmosphere in equilibrium with magma ocean would be highly reducing.

Oxidized vs Reduced

- Standard definition - loss (oxidized) or gain (reduced) of an electron.
- H is a reducing agent, O is a oxidizing agent
- Scenarios:
  - Earth's core formed at least 30 Myr after CAI's (e.g. Nimmo & Kleine 2015).
  - H_2 nebula dissipated; initial H_2 rich atmosphere ablated.
  - Oxidation state driven by presence/absence of water - or previous presence of water forming FeO
  - Earth form's from material primary interior to the snowline presents a moderately reducing proto-Earth

Oxidized vs Reduced

- Standard definition - loss (oxidized) or gain (reduced) of an electron.
- H is a reducing agent, O is a oxidizing agent
- Scenarios:
  - Earth's core formed at least 30 Myr after CAI's (e.g. Nimmo & Kleine 2015).
  - H_2 nebula dissipated; initial H_2 rich atmosphere ablated.
  - Oxidation state driven by presence/absence of water.
  - Earth forms from material with contributions beyond nebular snowline (during magma ocean phase).
  - Current consensus model and is much more oxidizing.

Key Factors: C/N & Core Formation

- Solubility in silicate melt
  - ➡ C more soluble than N - oxidizing conditions
  - ➡ N more soluble than C - reducing conditions
- Affinity for Fe-rich metal
  - ➡ C partitions more strongly than N (factors of 100 - 10^4)
- Timing (before, during, after core formation)

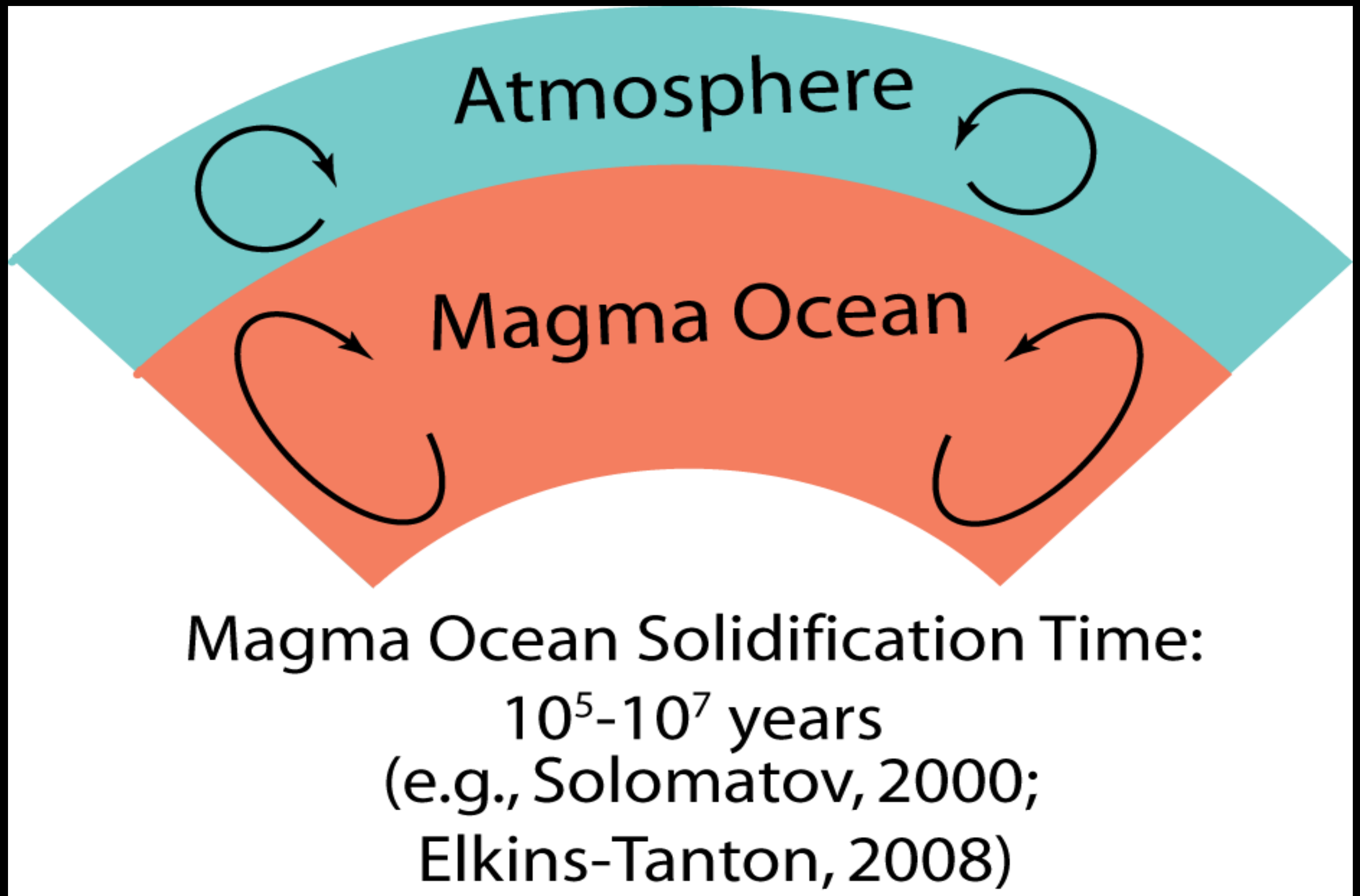
Model

1. C/N(initial) = 25

2. Chemical equilibrium with variable fraction of Fe/ Silicate mixture

➡ Forms metal/volatile rich silicate mixture

➡ overlying atmosphere



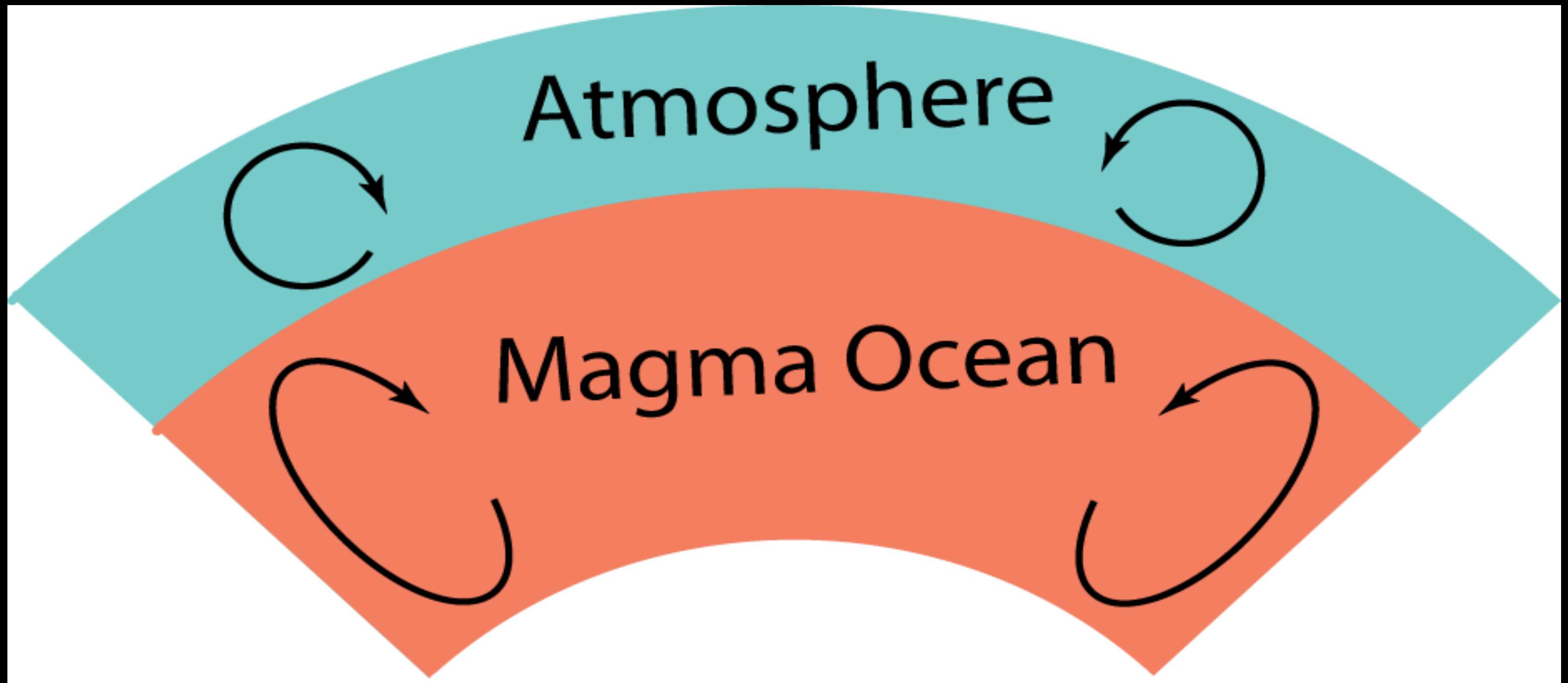
Model: M. Hirchmann
published in Bergin+ 2015

Model

3. Segregation and isolation of core

➡ mantle with C and N that do not go to core

➡ overlying atmosphere based on initial equilibrium



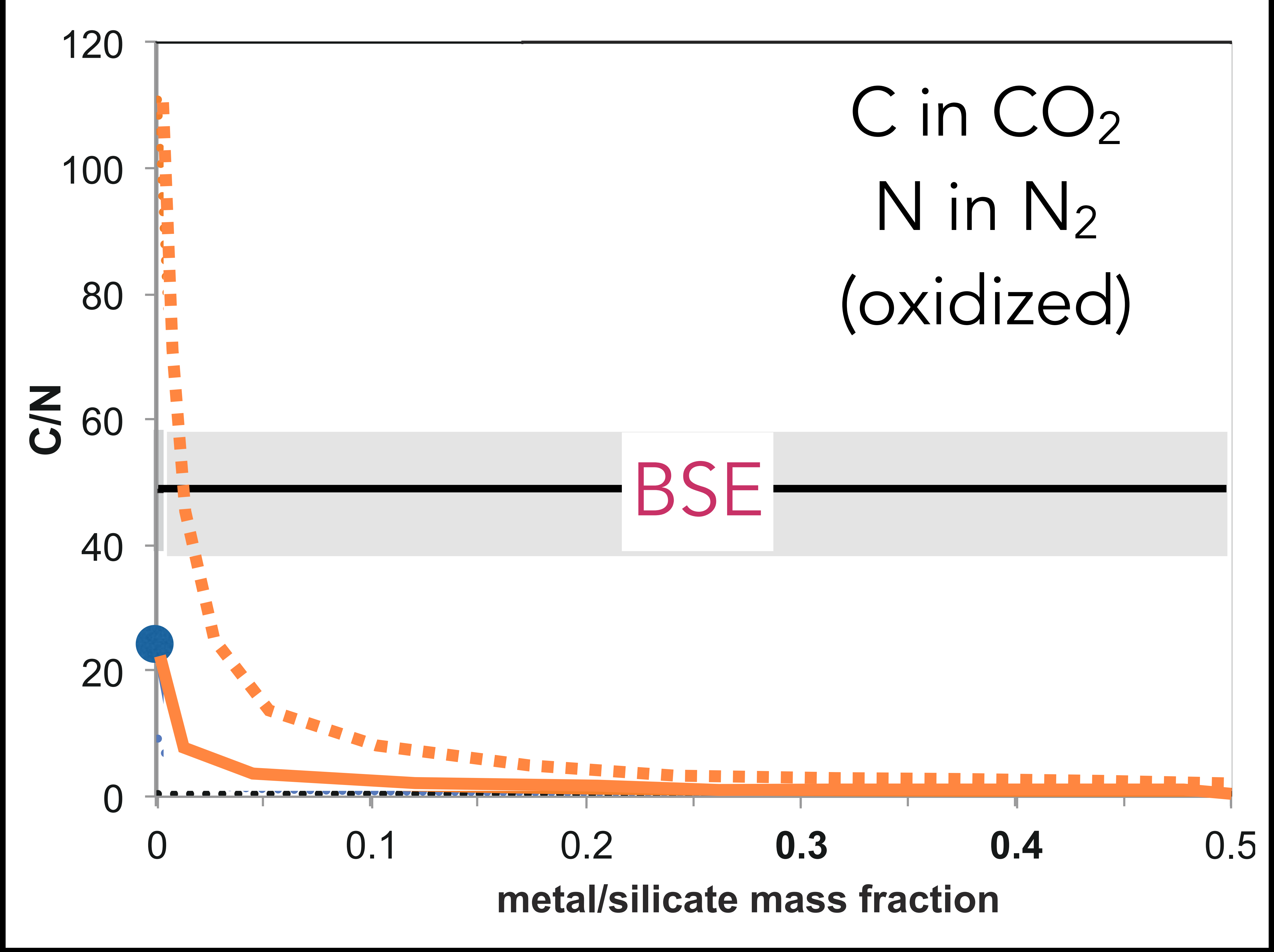
Magma Ocean Solidification Time:
10^5-10^7 years
(e.g., Solomatov, 2000;
Elkins-Tanton, 2008)

We consider two cases:

A - atmosphere returns to mantle to form BSE

B - atmosphere lost to space, mantle is BSE

Making a Habitable Planet



depletion of metal to core (time)

primordial atm. retained

- C segregates to core
- most N in atm.

➡ $C/N < (C/N)_{BSE}$

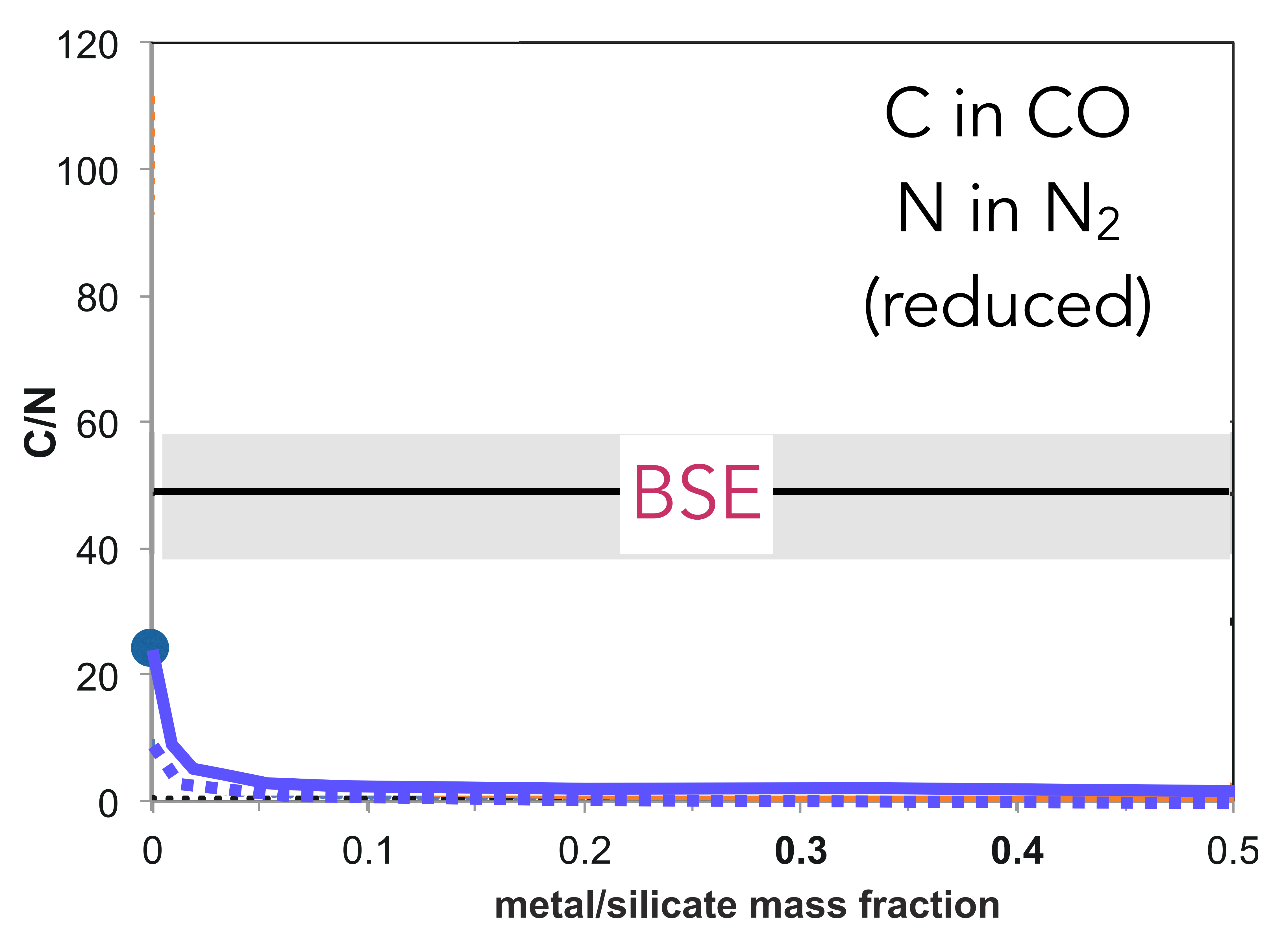
primordial atm. lost to space

- C segregates to core
- N in atm. lost

➡ $C/N < (C/N)_{BSE}$ except metal/silicate < 0.05

Bergin+ 2015

Making a Habitable Planet



depletion of metal to core (time)

primordial atm. retained

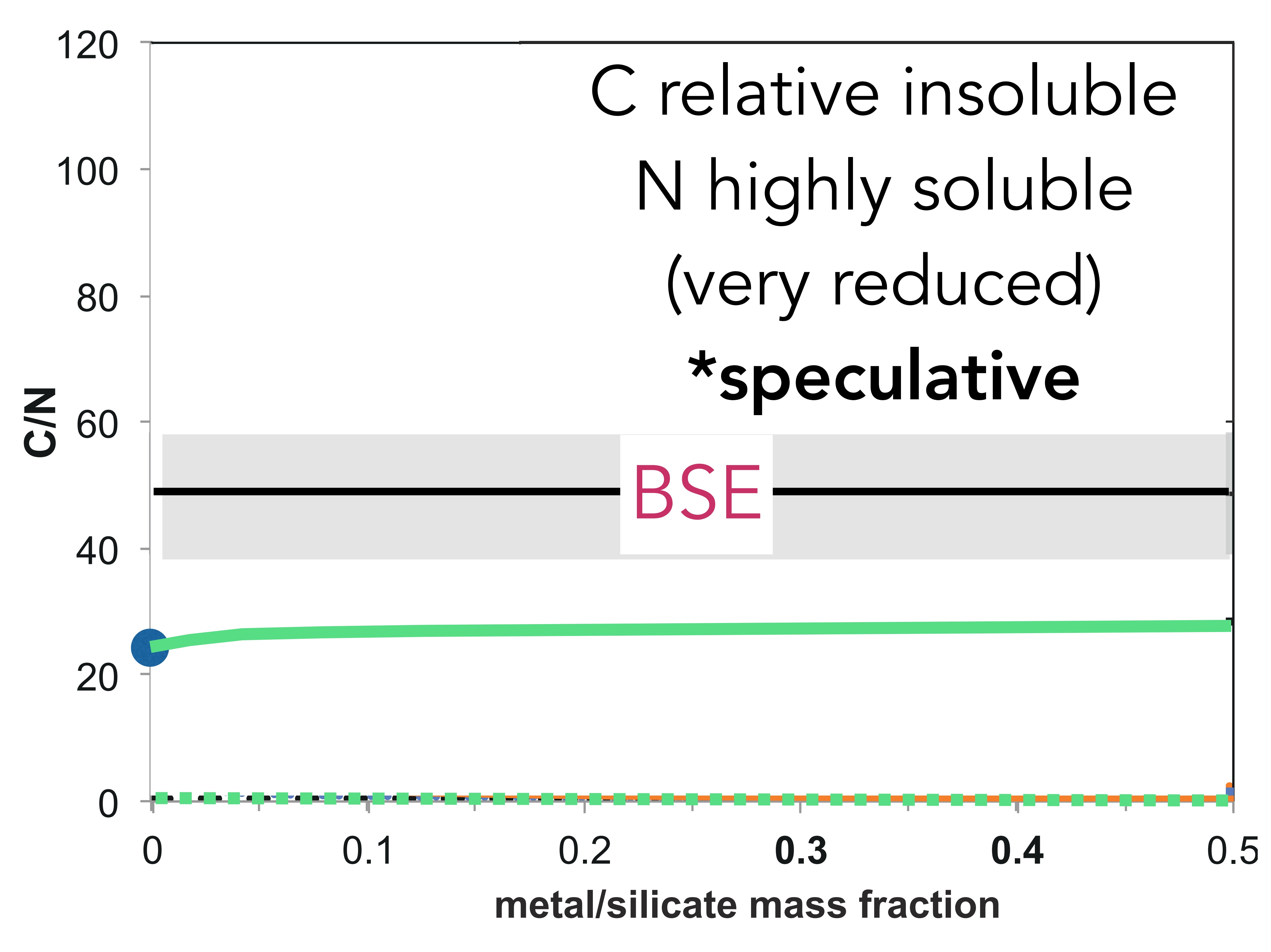
- Similar to last case

primordial atm. lost to space

- C less soluble
- C is lost along with N in atm. for low metal/Si

Bergin+ 2015

Making a Habitable Planet



depletion of metal to core (time)

primordial atm. retained

- Some N to core
- C in Atmosphere
- Retain initial C/N

primordial atm. lost to space

- C in atmosphere lost to space
- C/N << $(C/N)_{BSE}$

Bergin+ 2015

IMPACT OF CORE FORMATION

- <u>Based on this model.</u>
- Earth's C and N likely supplied by materials that were a mixture of our cases - so at least reduced, if not oxidized
- magma-ocean related core formation (under most likely conditions) provides

➡ low C in mantle, high N in atmosphere — need loss of primordial atmosphere to account for high C/N ratio.

➡ see work with Schlicting and also Stewart regarding atmospheric loss.

MAKING A HABITABLE WORLD

- *What does this mean?*

➡ *Clearly it is complicated - but key processes are now isolated.*

➡ *Loss terms in disk - depend on thermal history.*

➡ *Loss terms in planetesimals - depends on availability of ^{26}Al.*

➡ *Loss terms in planets - depends on accretion history and chemical conditions.*

MAKING A HABITABLE WORLD

- *What does this mean?*
  - ➡ *Clearly it is complicated - but key processes are now isolated.*
  - ➡ *It is time to take it to the next step and explore what matters and when.*
  - ➡ *Astronomical data will be key - ALMA/JWST/NOEMA/SMA and exoplanetary atmospheric composition.*
  - ➡ *Young disk may be crucial - needs to be characterized.*
  - ➡ *Did not talk about is isotopes which are potential "fingerprints" of source terms in gas-free disk. More information there - and don't forget about O and N isotopes along with D/H.*

THANK YOU!

images: Hacar+ 2015; Pinte+ 2016; Louvet+ 2018
Andrews+ 2018; NOAA

WHAT ABOUT VOLATILE ISOTOPES

- Isotopic ratios enable exploration of potential planetesimal mixing in gas-free nebula.
- Did dry Earth get water/carbon from beyond snowline in the form of meteorites or comets?
- Solar system water has enhanced D/H - originated in cold reservoir (< 20 K; Cleeves et al. 2014).
- Earth has D/H ratio commensurate with meteorites, but one comet (Hartley 2; Hartogh et al. 2011) has a comparable ratio.

➡ Hartley 2 has factor of ~2 higher $^{15}N/^{14}N$ ratio (Shinnake et al. 2016).

➡ Dynamical models (Morbidelli et al. 2000) show that cometary contribution is difficult. But pebbles…..

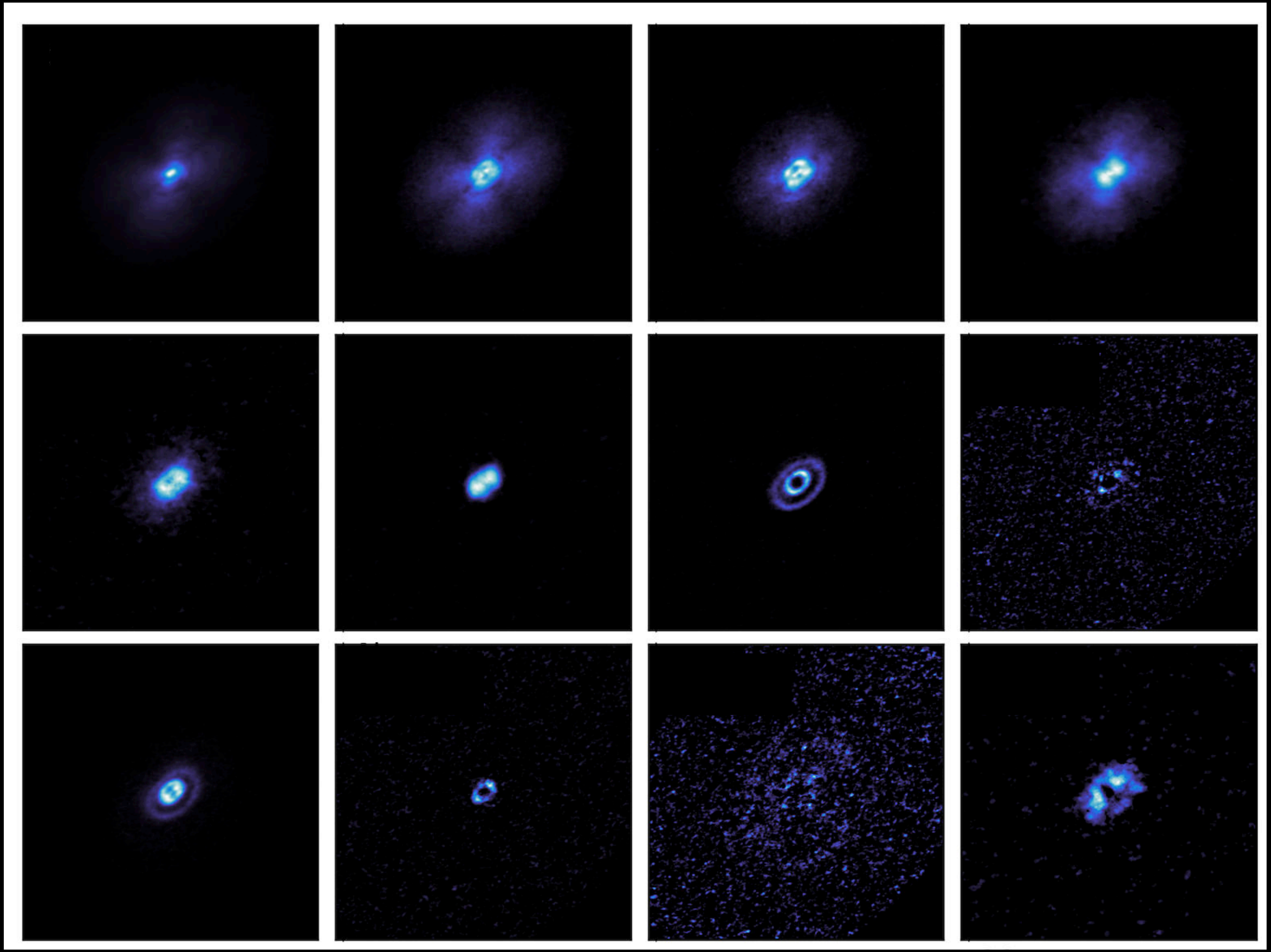
THE FUTURE

- *ALMA still in operation - great for C and N (less so for water)*
- *JWST (2021) 2-28 μm (R = Δλ/λ ~ 3000)*

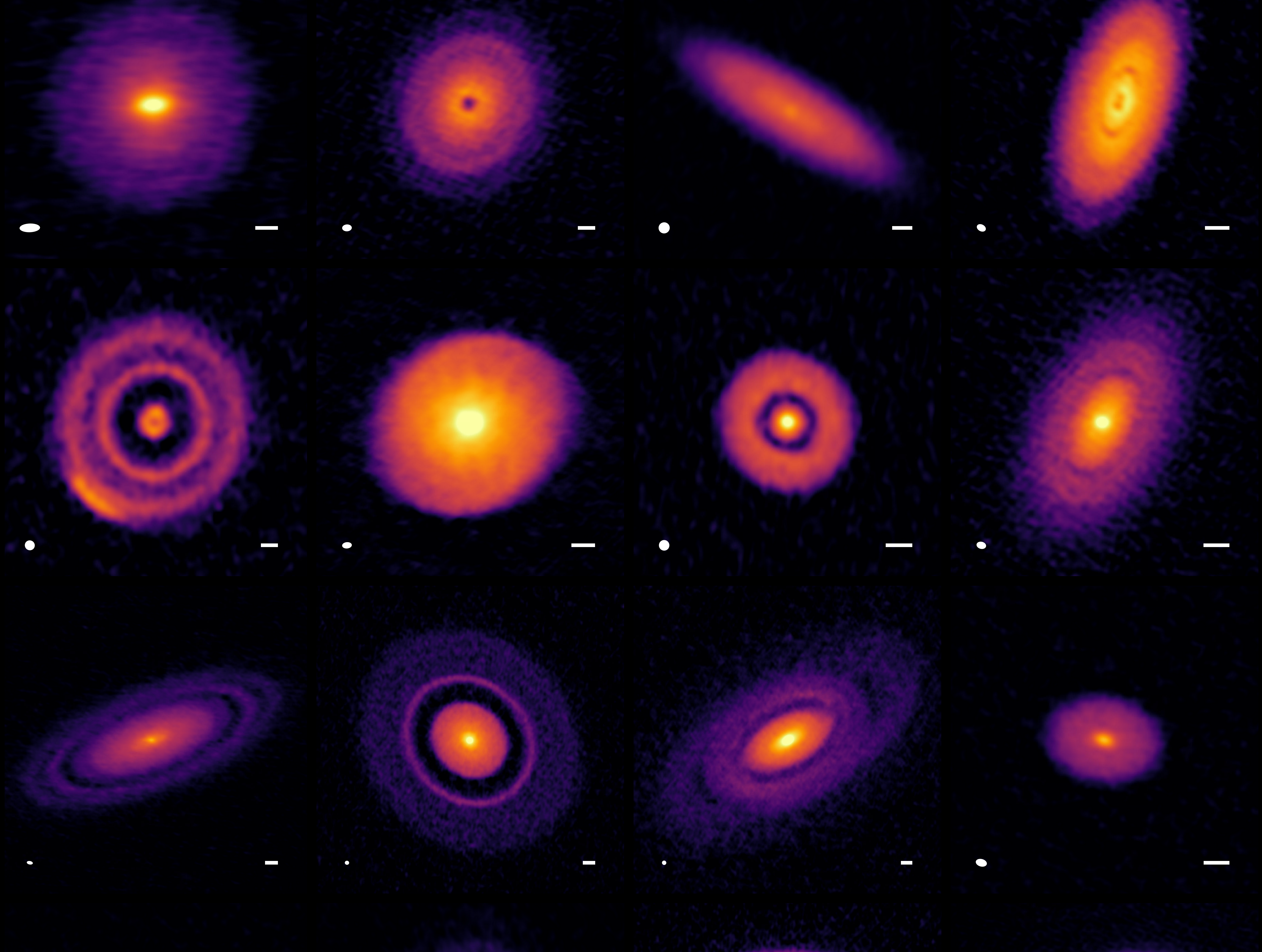
➡ *Provides access to emission from volatiles (CO_2, H_2O) arising from terrestrial planet formation zone*

- *Origins Space Telescope (mission proposed to decadal survey, 2030?) 25-588 μm (R ~ 300000)*

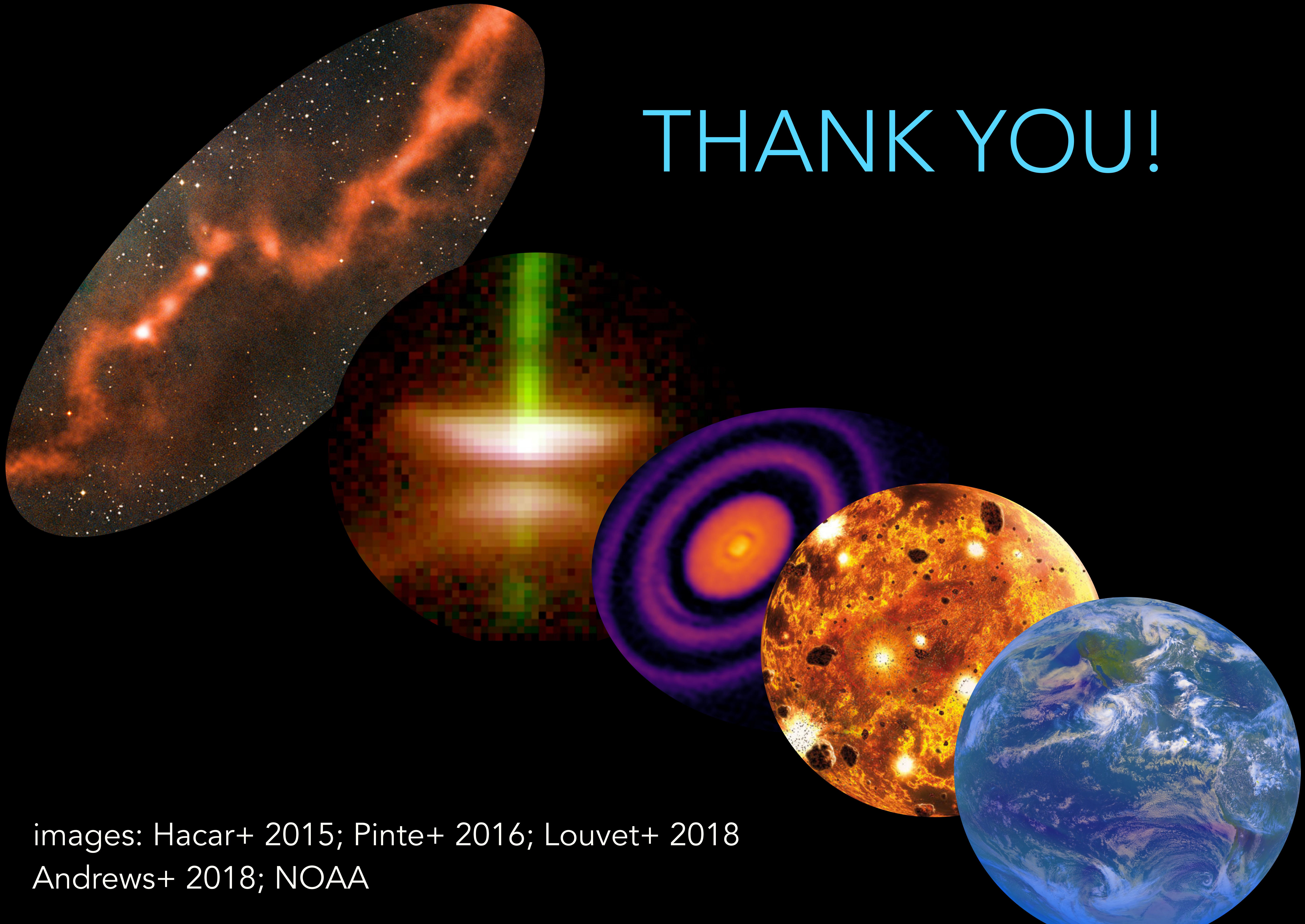
➡ *capable of surveying water vapor/ice, HD in 1000 disks to provide needed statistics to link to exoplanet inventory.*



“The Chemistry of Planet Formation” (PI: Öberg, Aikawa, Guzman, Walsh, Bergin)



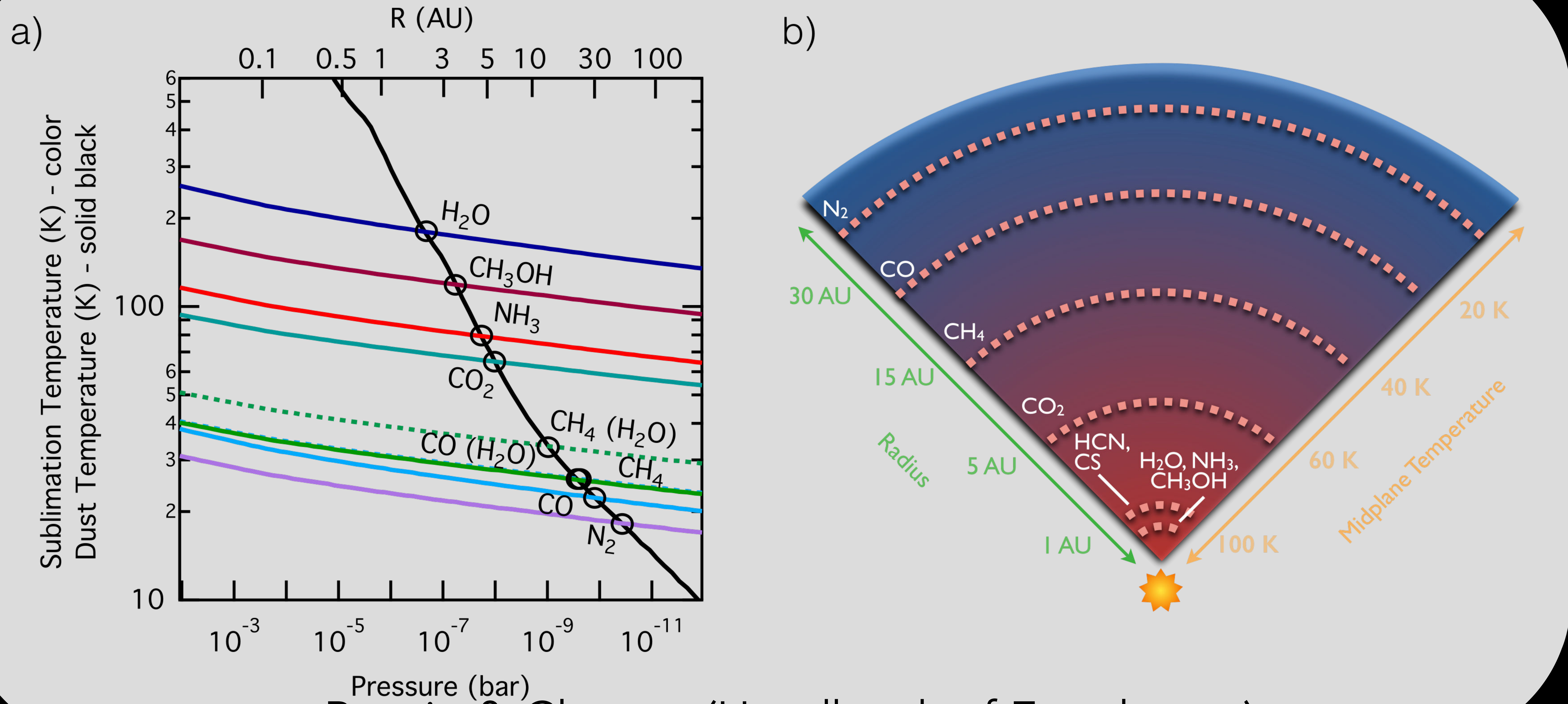
THANK YOU!



images: Hacar+ 2015; Pinte+ 2016; Louvet+ 2018
Andrews+ 2018; NOAA

SNOWLINES AND CHEMICAL GRADIENTS

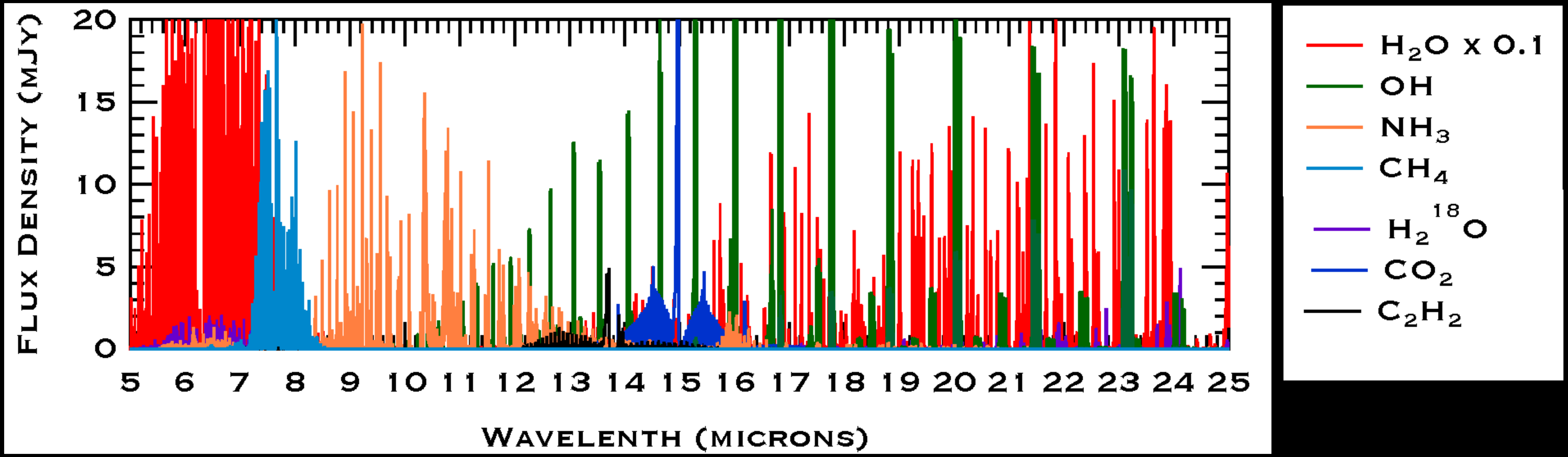
- To date clear focus on connective tissue has been the C/O ratio and snowlines (Öberg, Murray-Clay, & Bergin 2011).



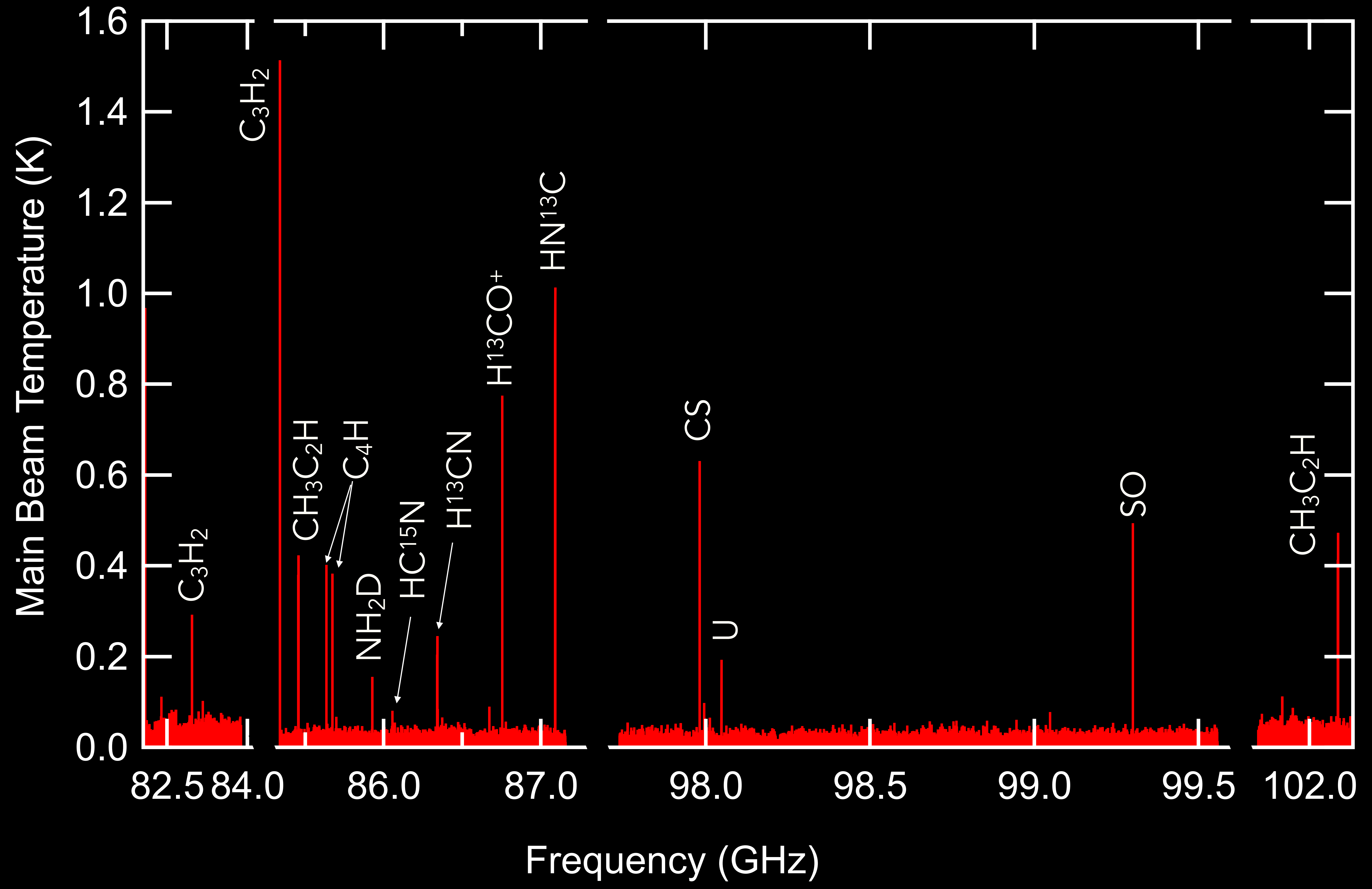
Bergin & Cleeves (Handbook of Exoplanets)

Going Forward

- JWST

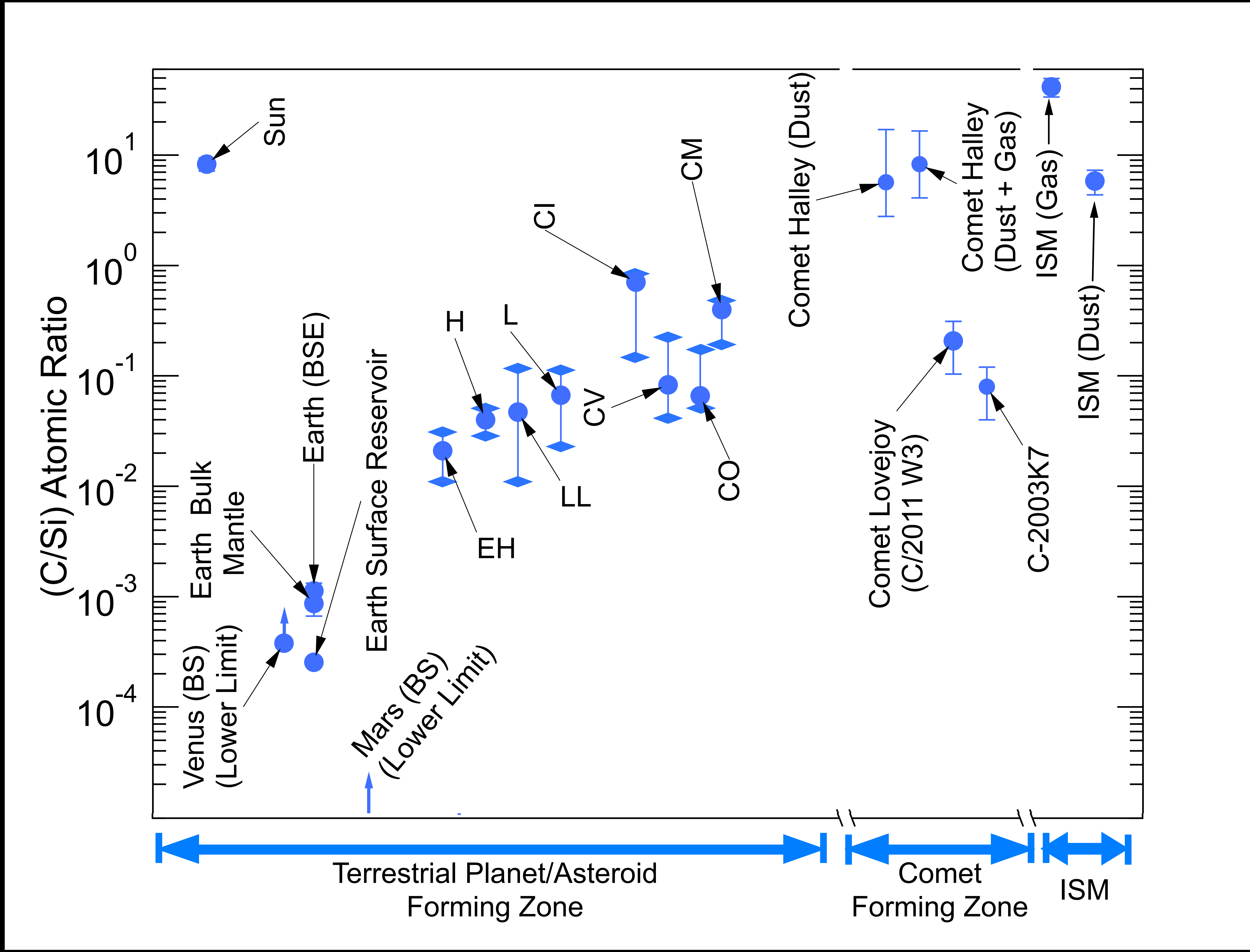


- More observations with ALMA will improve statistics on CO column into 10 AU.
- HD observations with SOFIA/HIRMES to unlock C/H and O/H
- Exoplanets Spectra from JWST and large telescopes



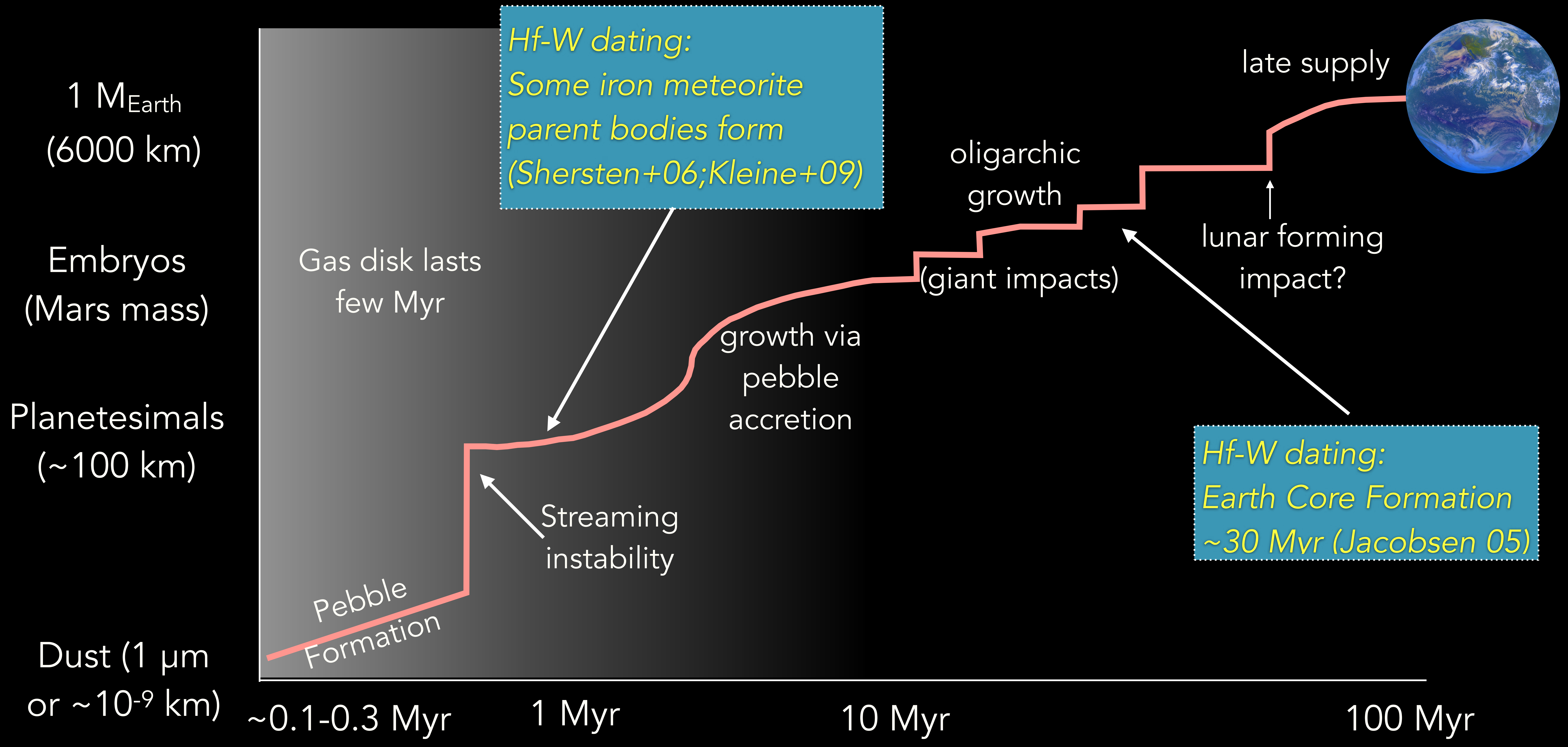
Main Beam Temperature (K)
1.6
1.4
1.2
1.0
0.8
0.6
0.4
0.2
0.0
C_3H_2
C_3H_2
CH_3C_2H
C_4H
NH_2D
$HC^{15}N$
$H^{13}CN$
$H^{13}CO^+$
$HN^{13}C$
CS
U
SO
CH_3C_2H
82.5
84.0
86.0
87.0
98.0
98.5
99.0
99.5
102.0
Frequency (GHz)

What about Terrestrial Worlds?



Bergin +2015

Talking about time...



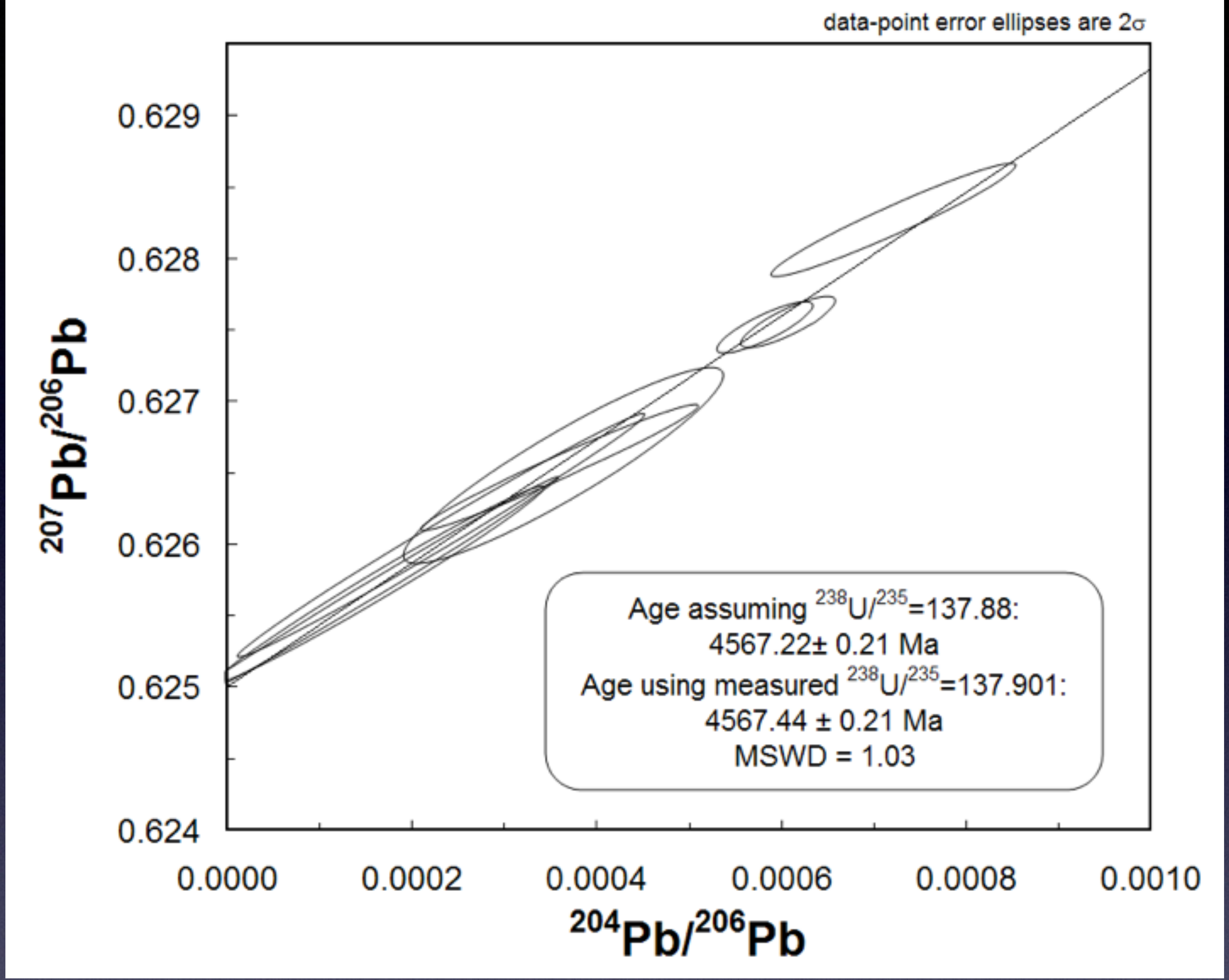
adapted from Meech & Raymond 2019; see also Johansen & Lambrechts 2017 and Morbidelli 2018

Radiometric Dating: Absolute Age

- Different atoms have different half-lives
  - ➡ Uranium-238 to Lead-206 4.47 billion years
  - ➡ Potassium-40 to Argon-40 1.25 billion years
  - ➡ Carbon-14 to Nitrogen-14 5730 years

Circuitous Routes: U-Th-Pb decay

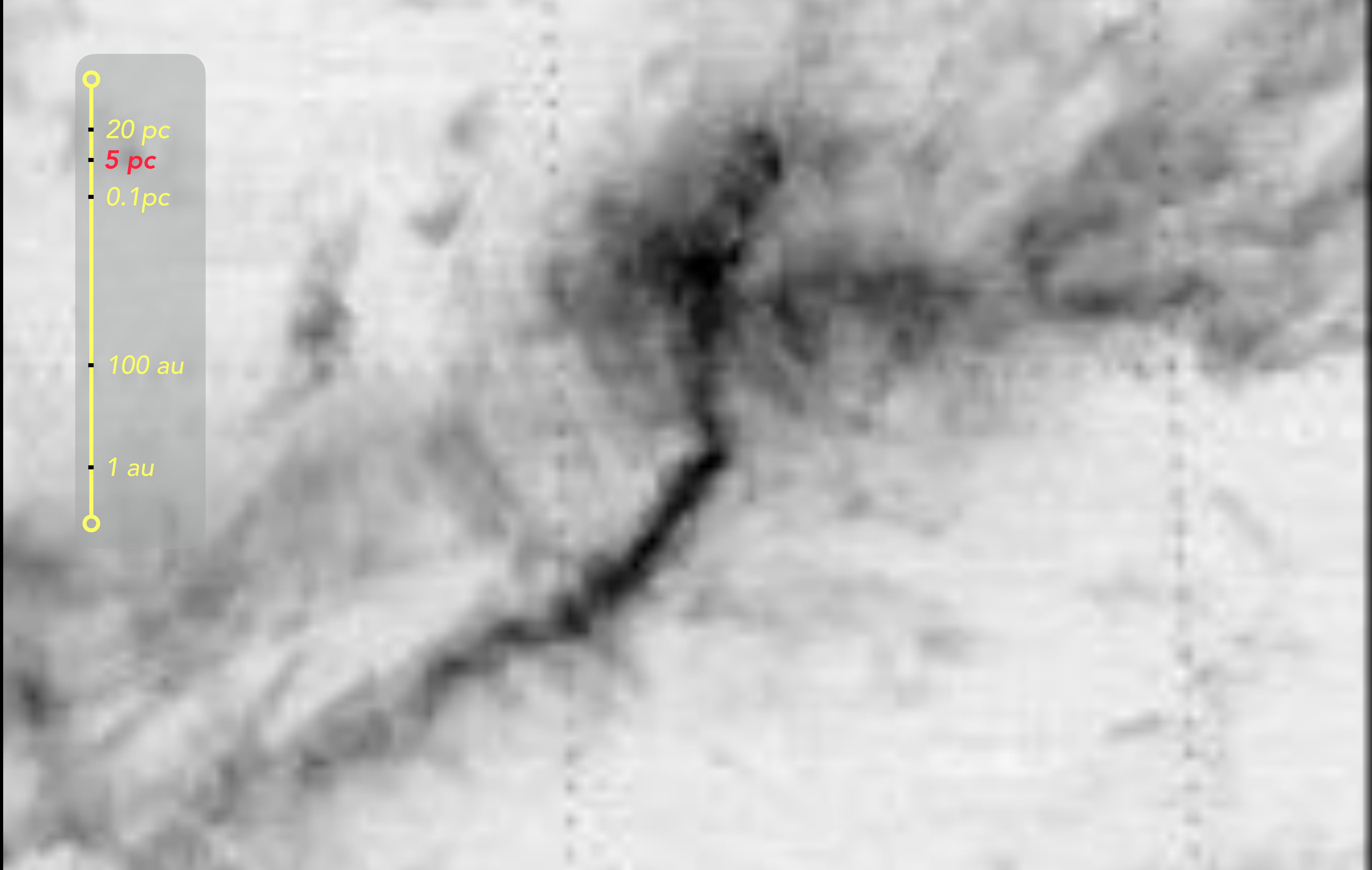
Element	U-238 series							Th-232 series					U-235 series				
Neptunium																	
Uranium	U-238 4.47×10^9 y		U-234 2.48×10^5 y										U-235 7.04×10^8 y				
Protactinium		Pa-234 1.18 min												Pa-231 3.25×10^4 y			
Thorium	Th-234 24.1 d		Th-230 7.52×10^4 y					Th-232 1.40×10^{10} y		Th-228 1.91 y			Th-231 25.5 hrs		Th-227 18.7 d		
Actinium									Ac-228 6.13 hrs					Ac-227 21.8 y			
Radium			Ra-226 1.62×10^3 y					Ra-228 5.75 y		Ra-224 3.66 d					Ra-223 11.4 d		
Francium																	
Radon			Rn-222 3.82 d							Rn-220 55.6 s					Rn-219 3.96 s		
Astatine																	
Polonium			Po-218 3.05 min		Po-214 1.64×10^{-4} s		Po-210 138 d			Po-216 0.15 s	64%	Po-212 3.0×10^{-7} s			Po-215 1.78×10^{-3} s		
Bismuth				Bi-214 19.7 min		Bi-210 5.01 d					Bi-212 60.6 min					Bi-211 2.15 min	
Lead			Pb-214 26.8 min		Pb-210 22.3 y		Pb-206 Stable lead isotope			Pb-212 10.6 hrs	36%	Pb-208 Stable lead isotope			Pb-211 36.1 min		Pb-207 Stable lead isotope
Thallium											Tl-208 3.05 min					Tl-207 4.77 min	



Amelim

- modern methods: earliest known solids Calcium Aluminum rich inclusions - first solids to form
- Over 70 meteorites have ages of 4.53-4.57 Billion Years


20 pc
5 pc
0.1pc
100 au
1 au


20 pc
5 pc
0.1pc
100 au
1 au